Intro to the Cosmic Microwave Background

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BNL
June 20, 2017

Cosmological paradigm

Cosmological paradigm

The standard cosmological paradigm is an expanding Universe containing dark energy (Λ) and cold dark matter.

"ΛCDM"

Cosmological paradigm

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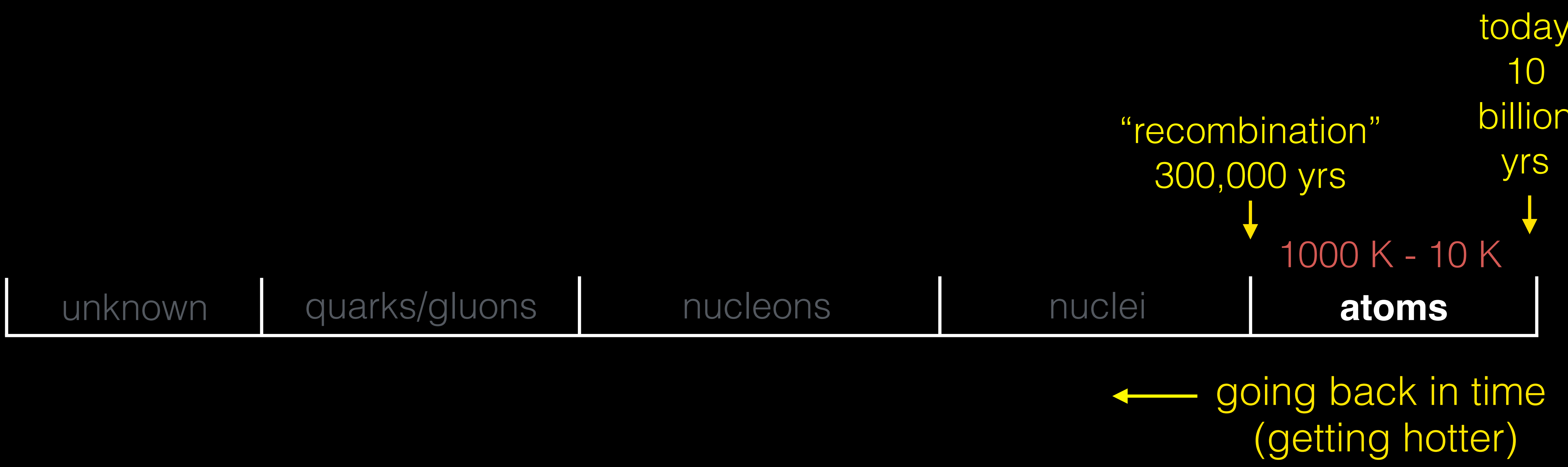
"ΛCDM"

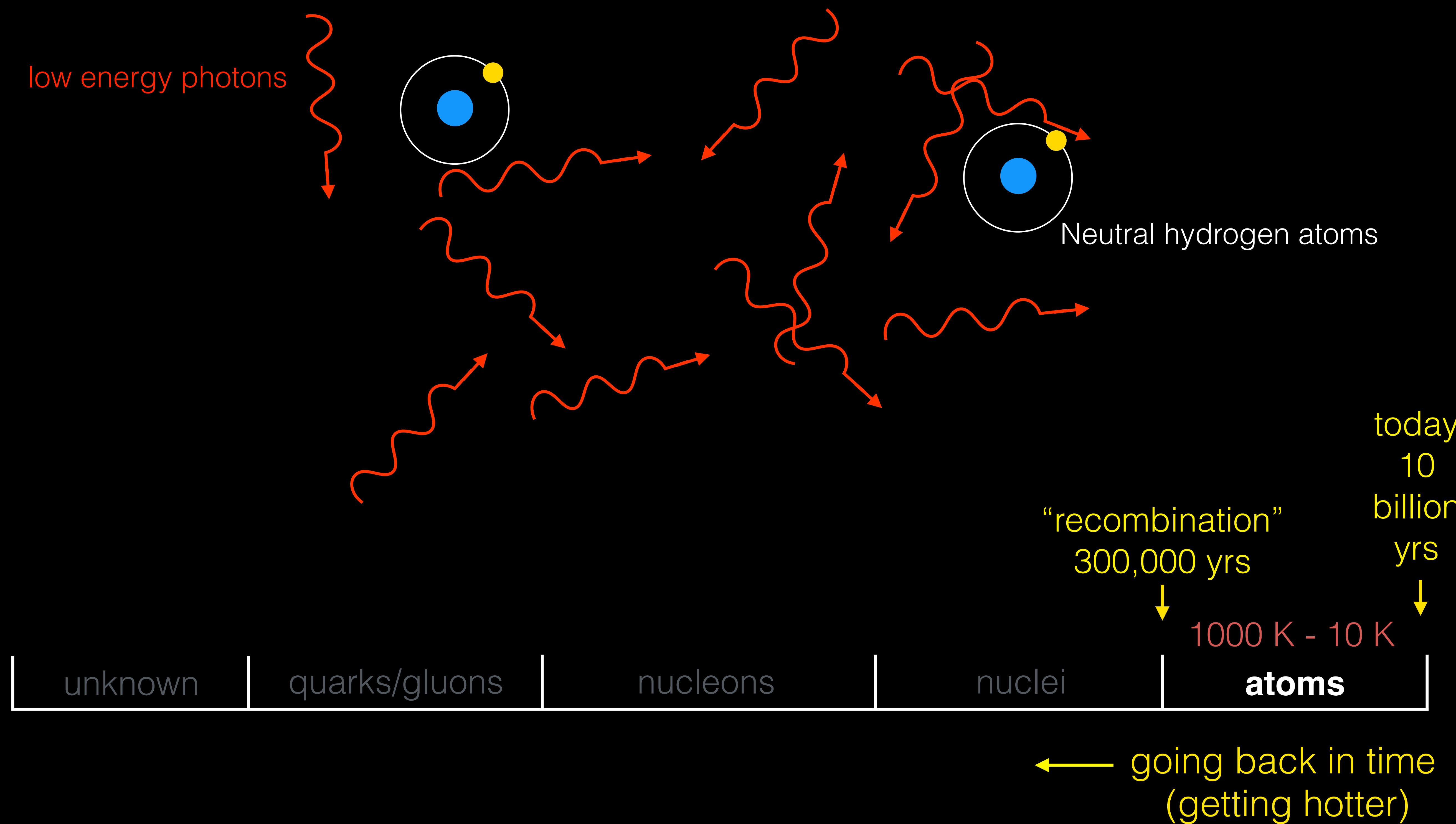
If the Universe is expanding, then it used to be smaller, denser, and hotter.

Thermal history of the Universe

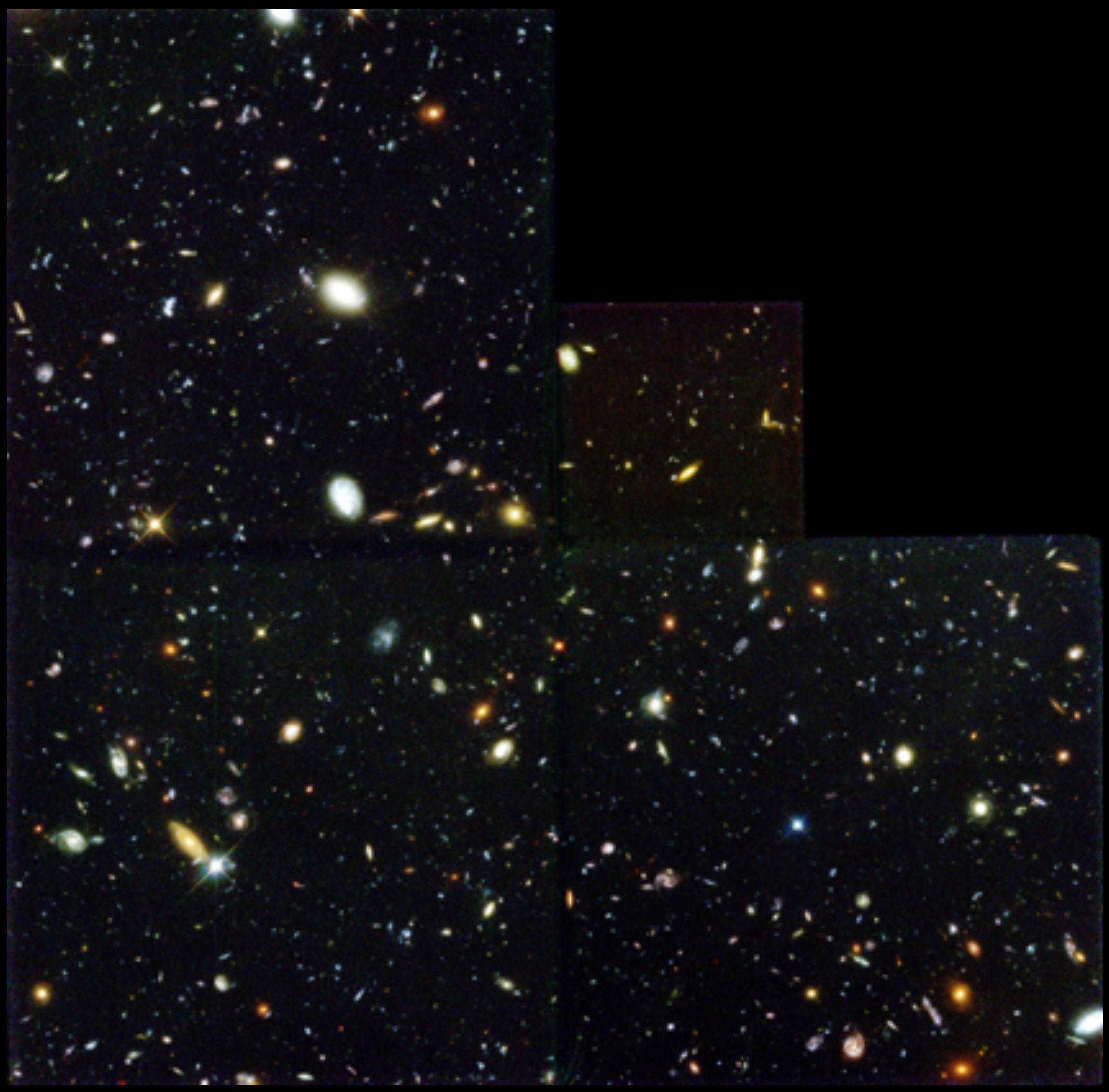


Thermal history of the Universe

The universe at **low** temperature



Thermal history of the Universe



Hubble Deep Field

- sees back to first generations of stars and galaxies
- between the present and when the Universe is ~300,000 years old, the Universe is cool enough that neutral atoms can exist

today
10 billion yrs

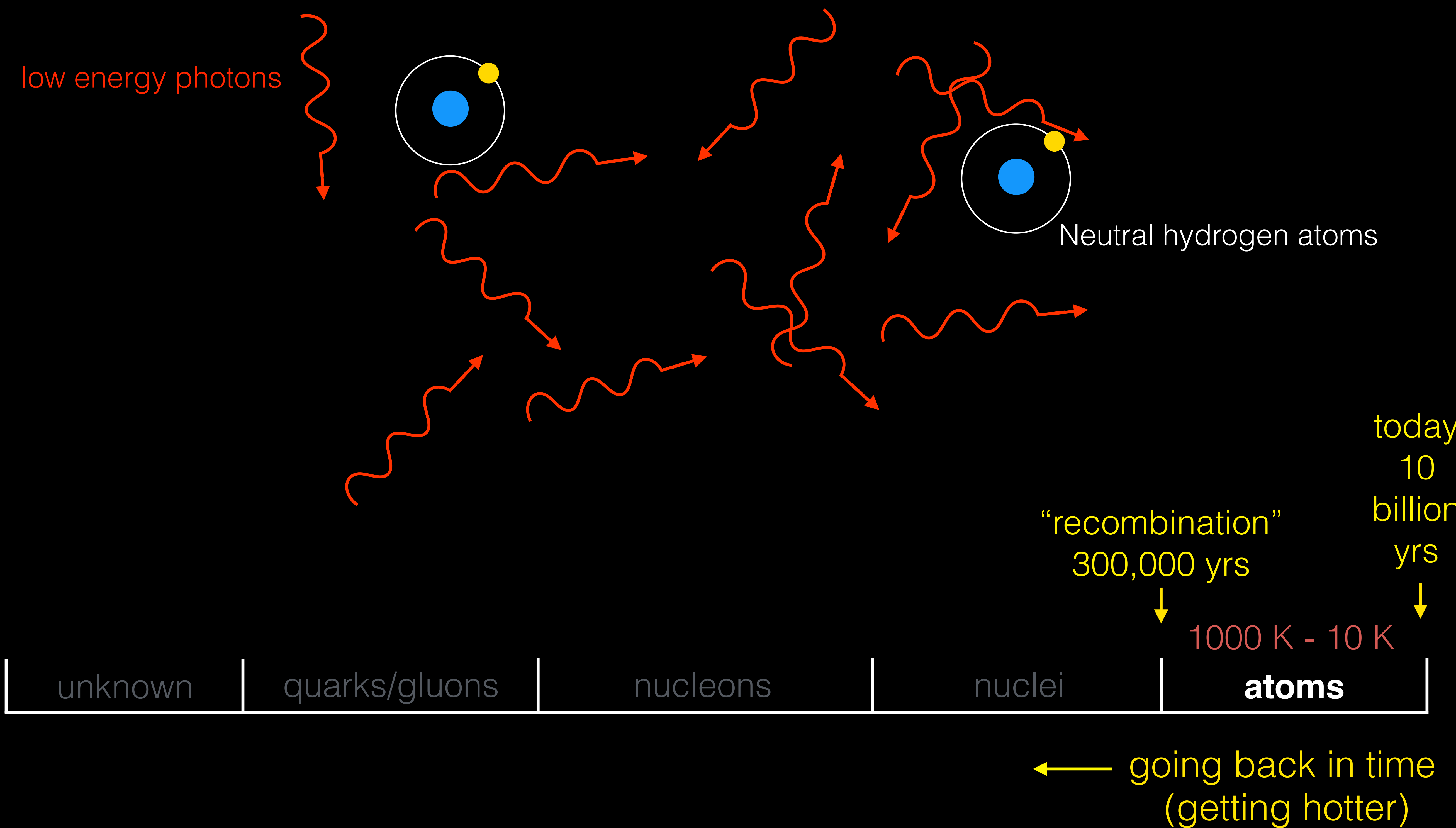
“recombination”
300,000 yrs

1000 K - 10 K

unknown	quarks/gluons	nucleons	nuclei	**atoms**

← going back in time
(getting hotter)

Thermal history of the Universe



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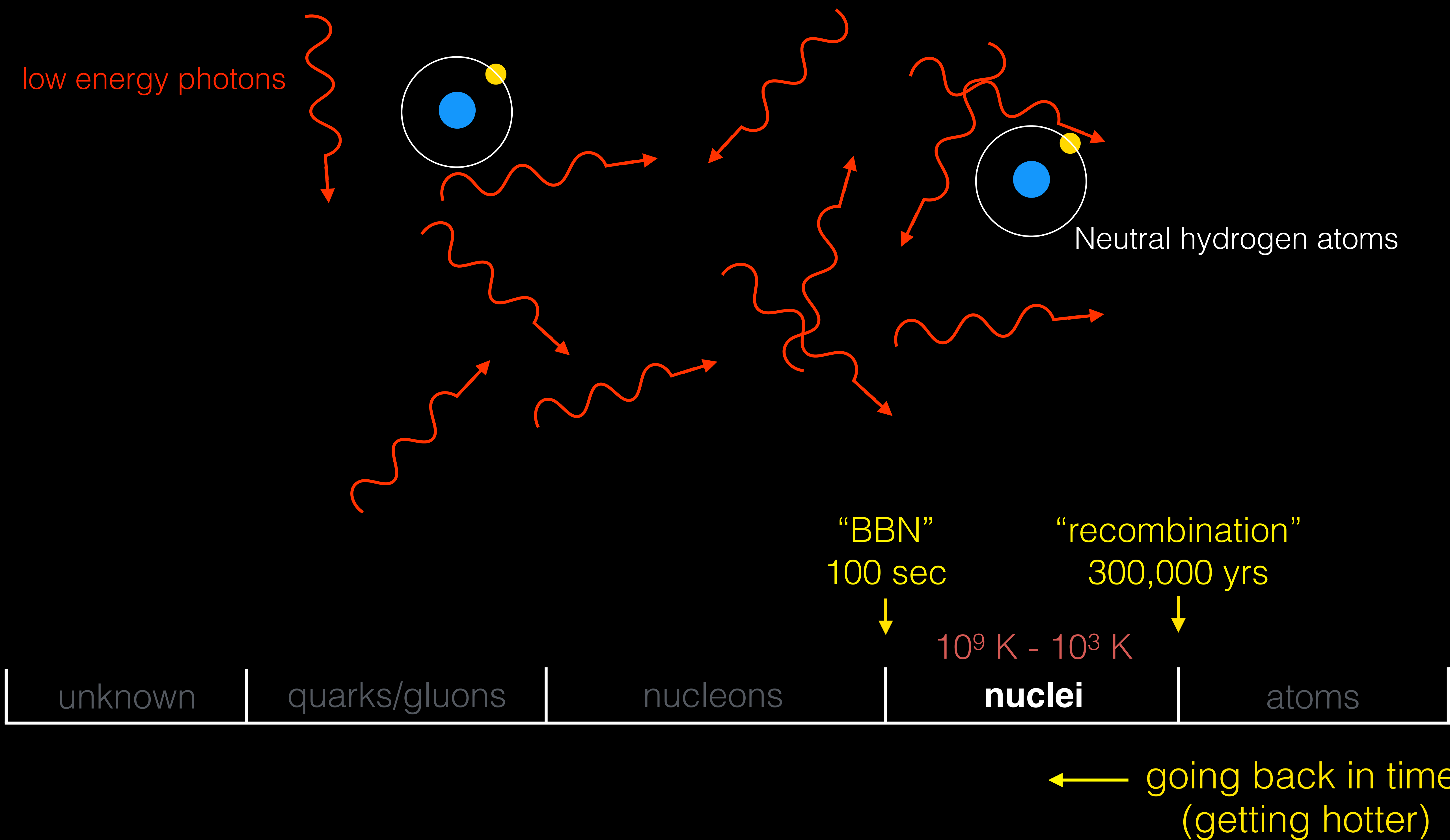

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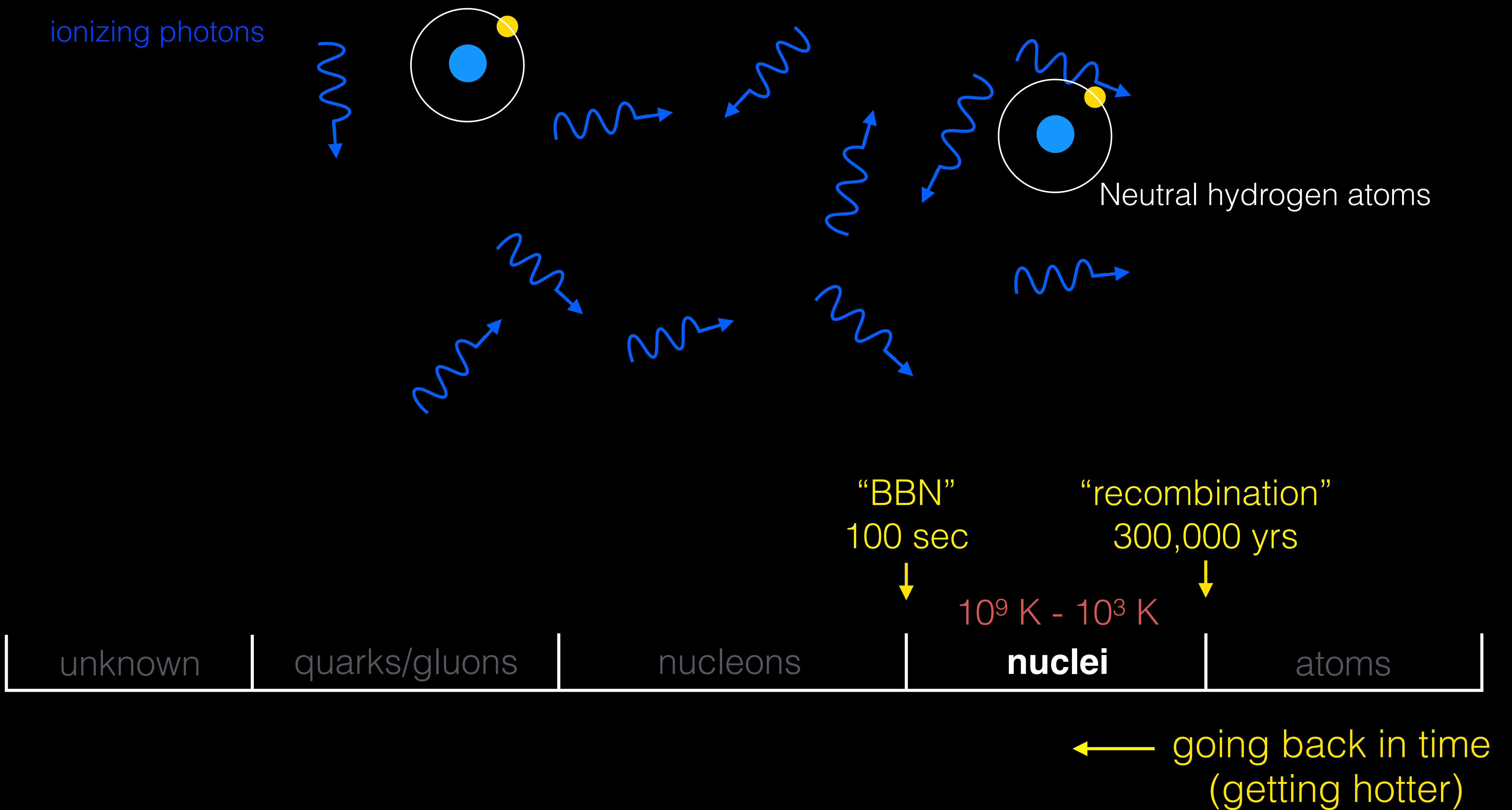
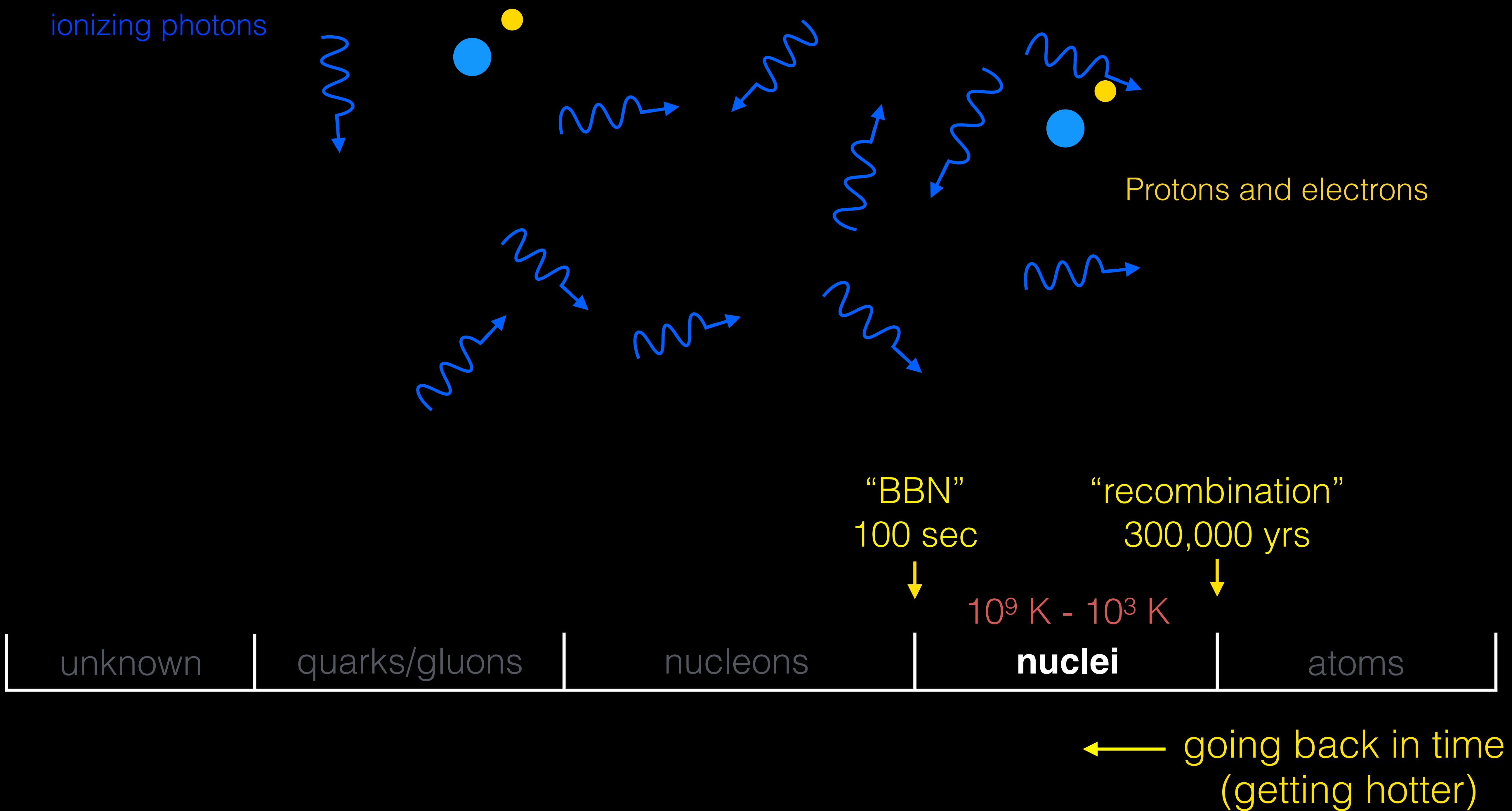
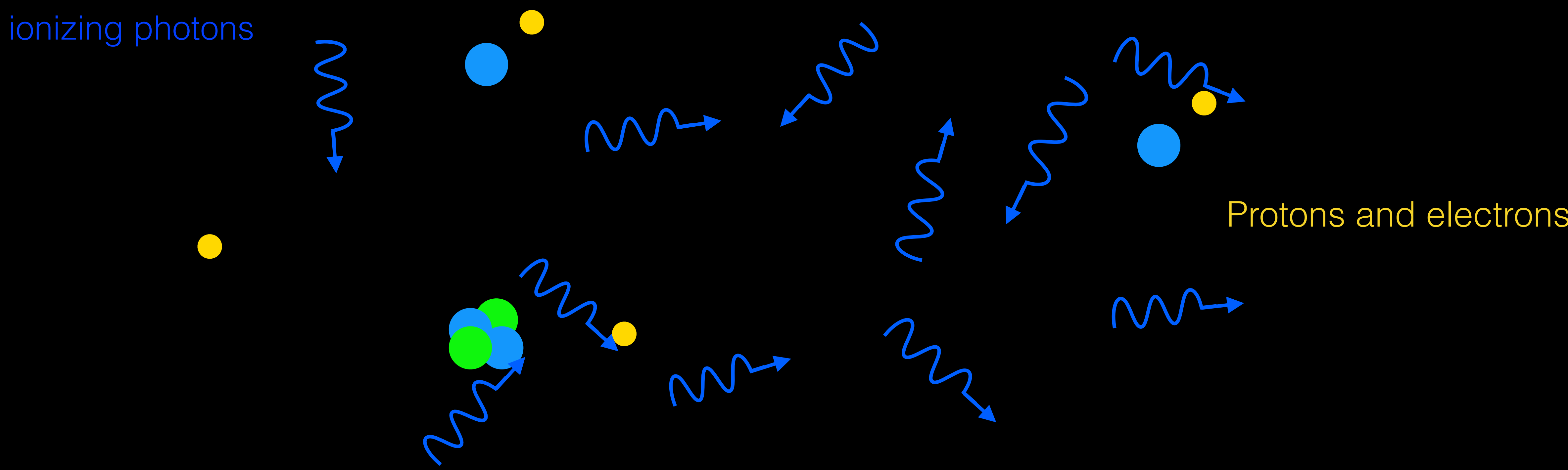


Thermal history of the Universe



Thermal history of the Universe

The universe at **high** (>3000 K) temperature:
hydrogen and helium plasma + photons = the “photon/baryon fluid”



“BBN”
100 sec

“recombination”
300,000 yrs

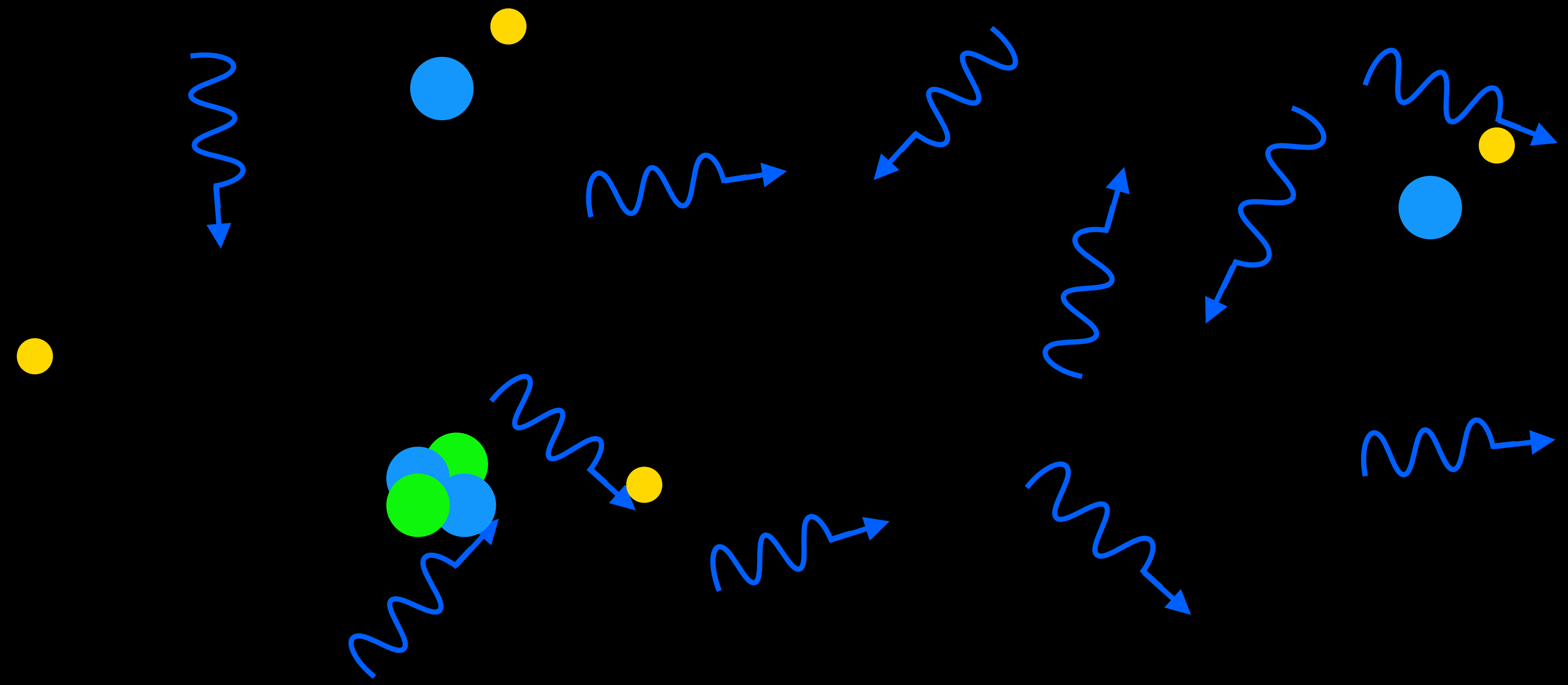
10^9 K - 10^3 K

unknown	quarks/gluons	nucleons	**nuclei**	atoms

← going back in time
(getting hotter)

Thermal history of the Universe

Free electrons have a high cross section to photons. Neutral hydrogen atoms do not. Efficient Thompson scattering makes the plasma opaque.



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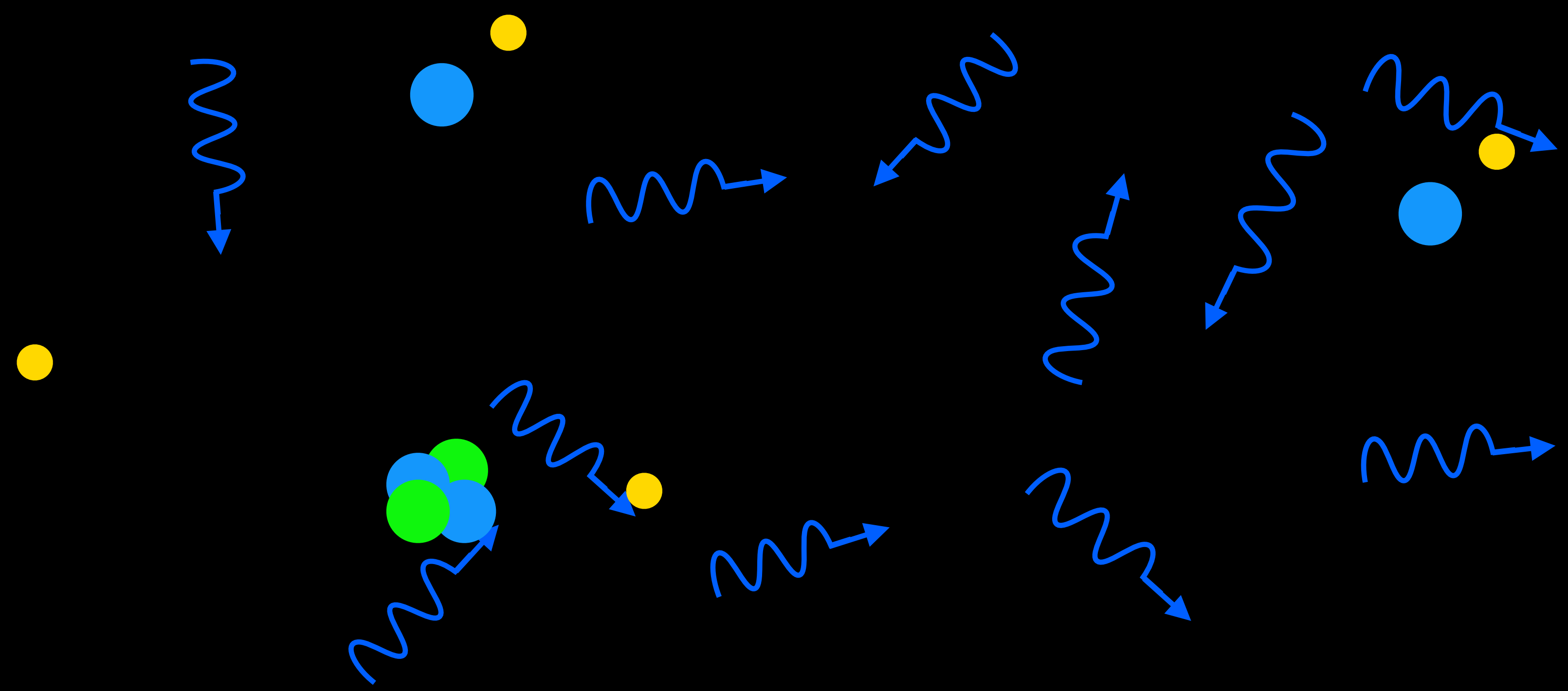
Thermal history of the Universe

Going forward in time…



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100 sec

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300,000 yrs

10^9 K - 10^3 K

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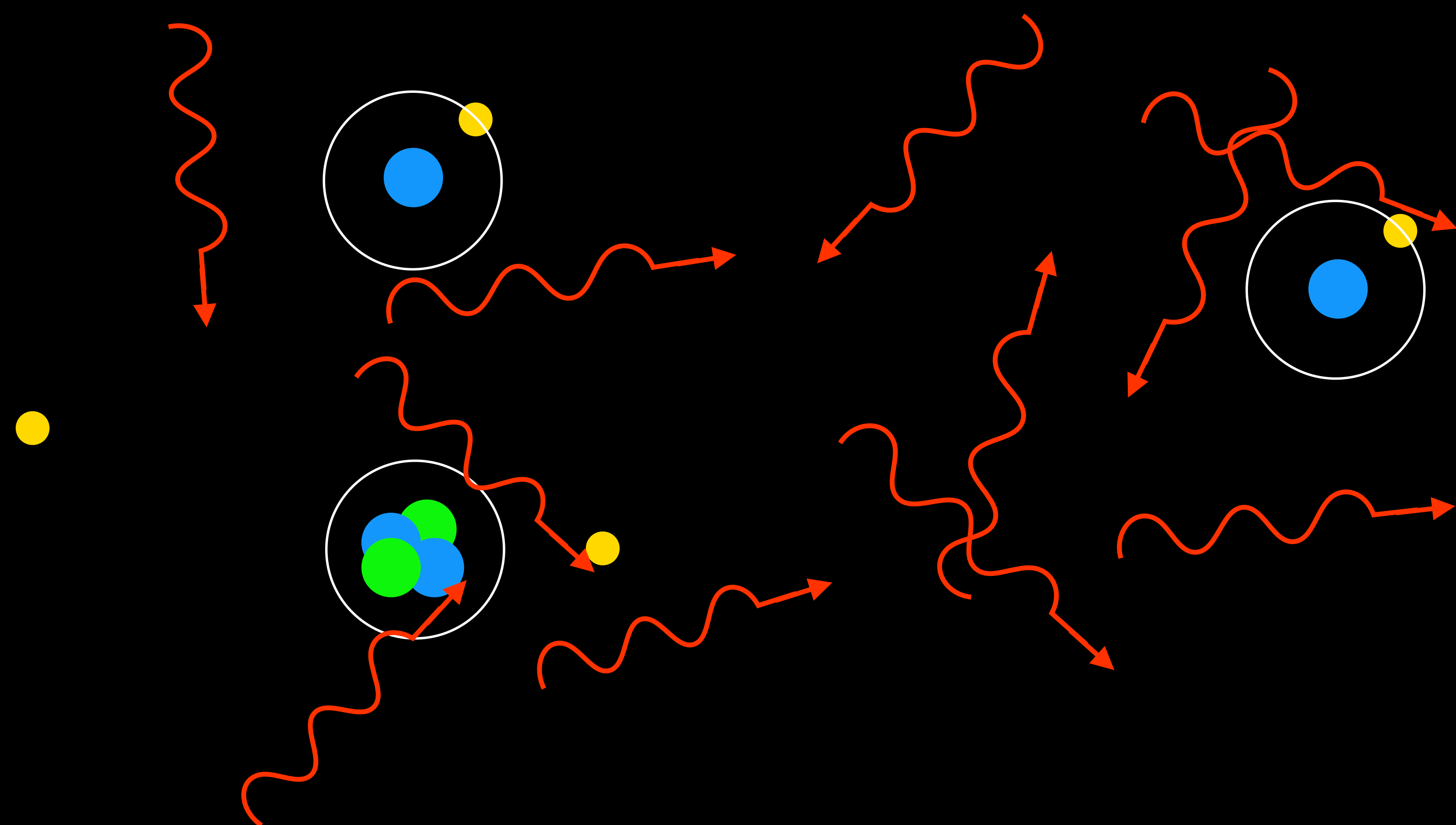
(getting hotter)

Thermal history of the Universe

Going forward in time, when the Universe cools to ~3000 K, the protons and electrons "recombine," and the photons travel unimpeded through space.



"BBN" 100 sec	"recombination" 300,000 yrs

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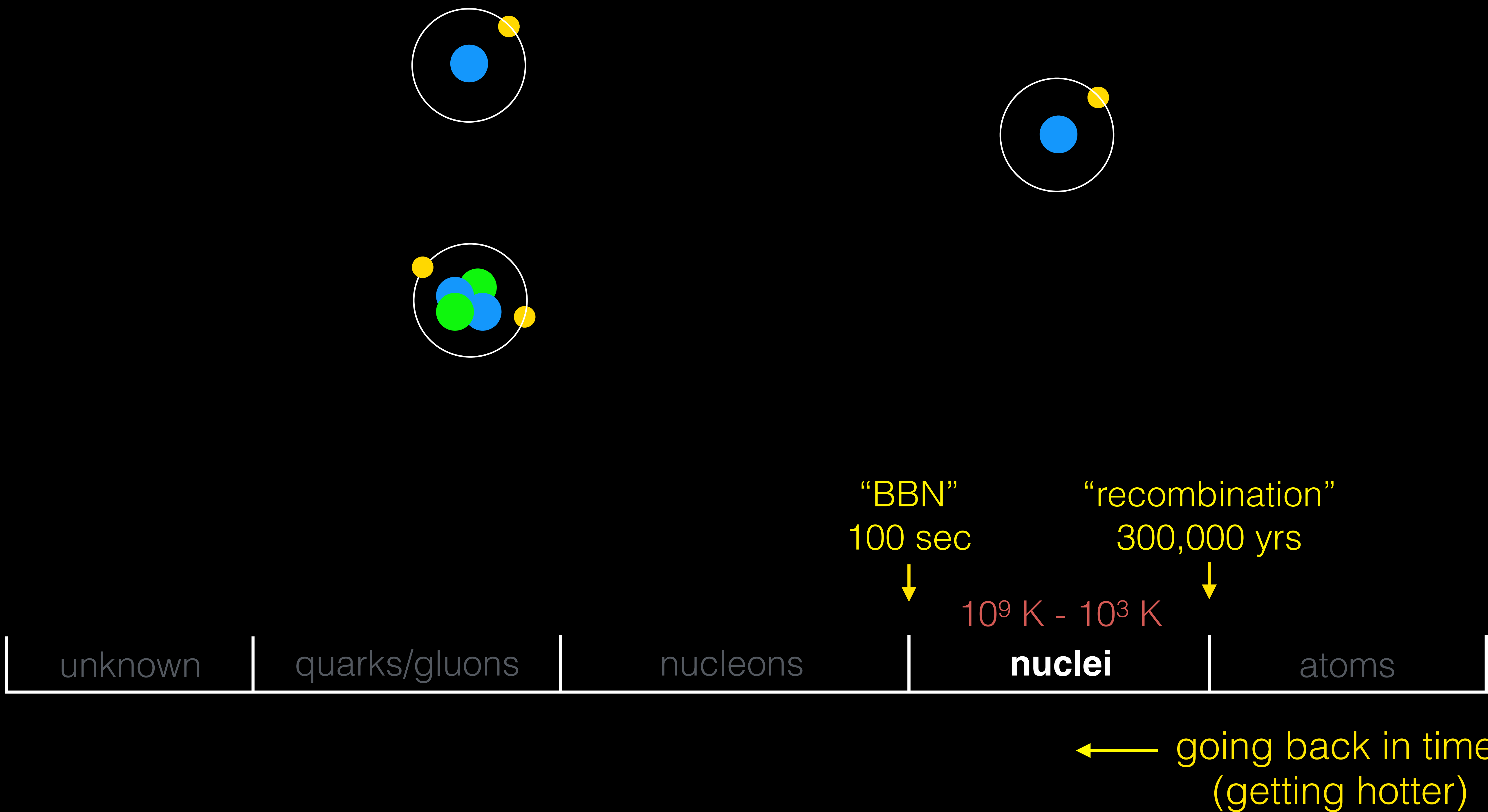
Thermal history of the Universe

The photons heading in the right direction find their way to Earth.



Cosmic Microwave Background

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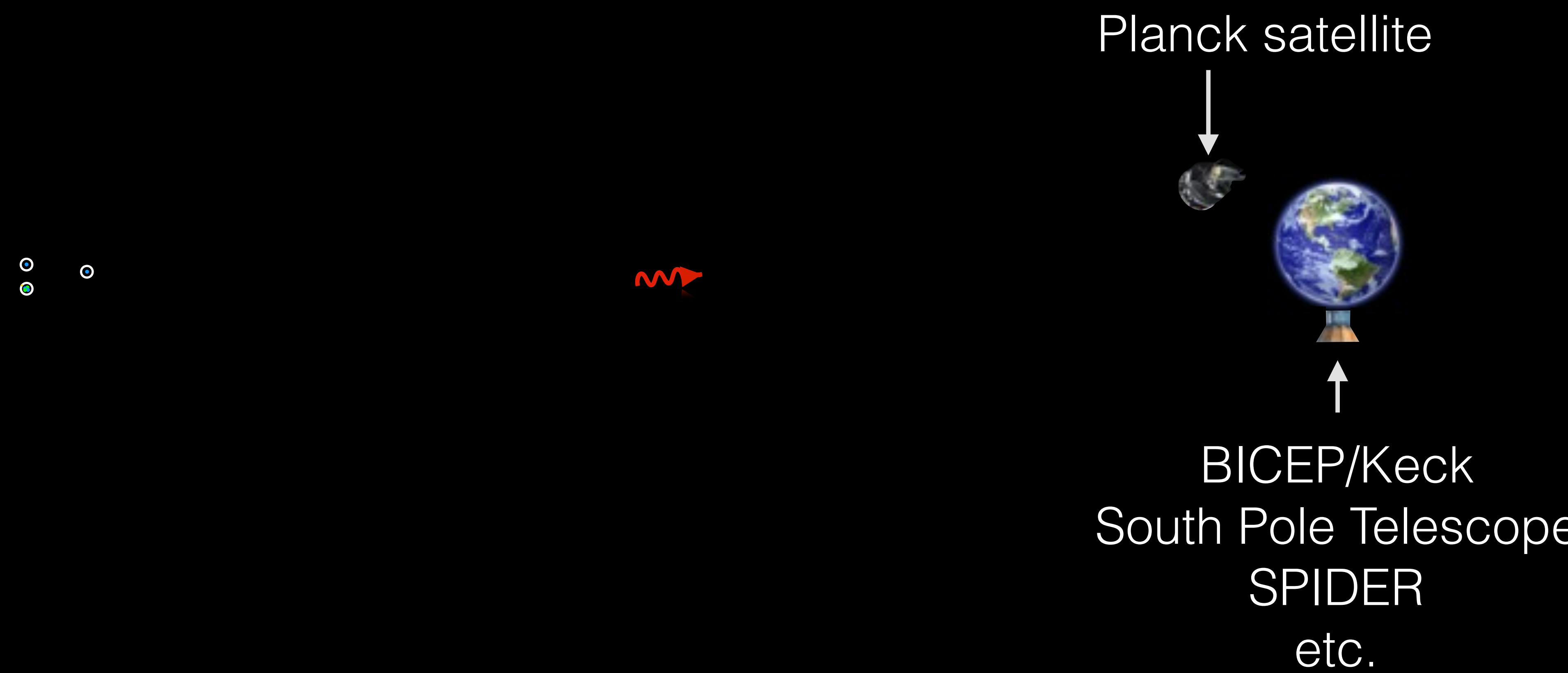
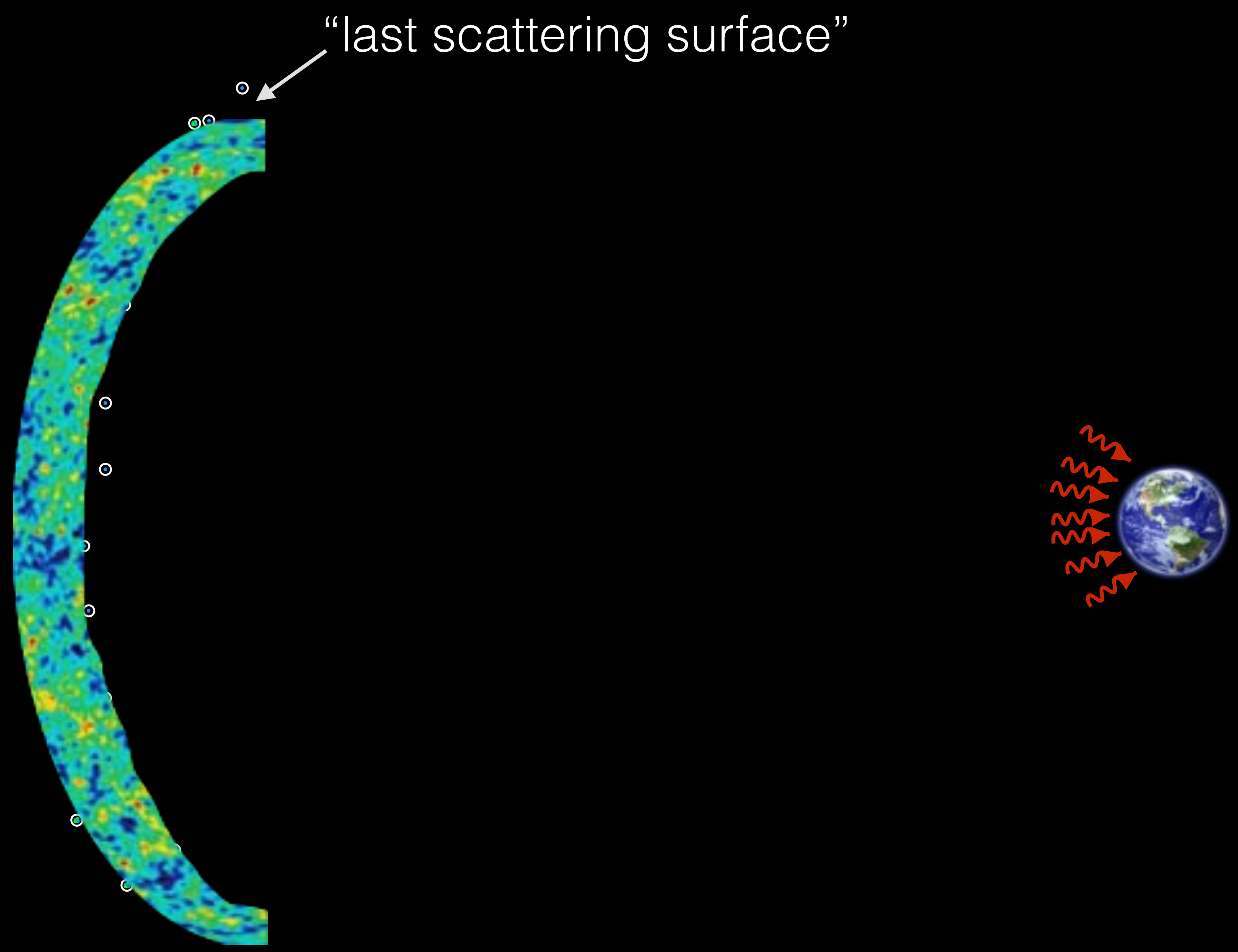


Cosmic Microwave Background

This is the Cosmic Microwave Background!

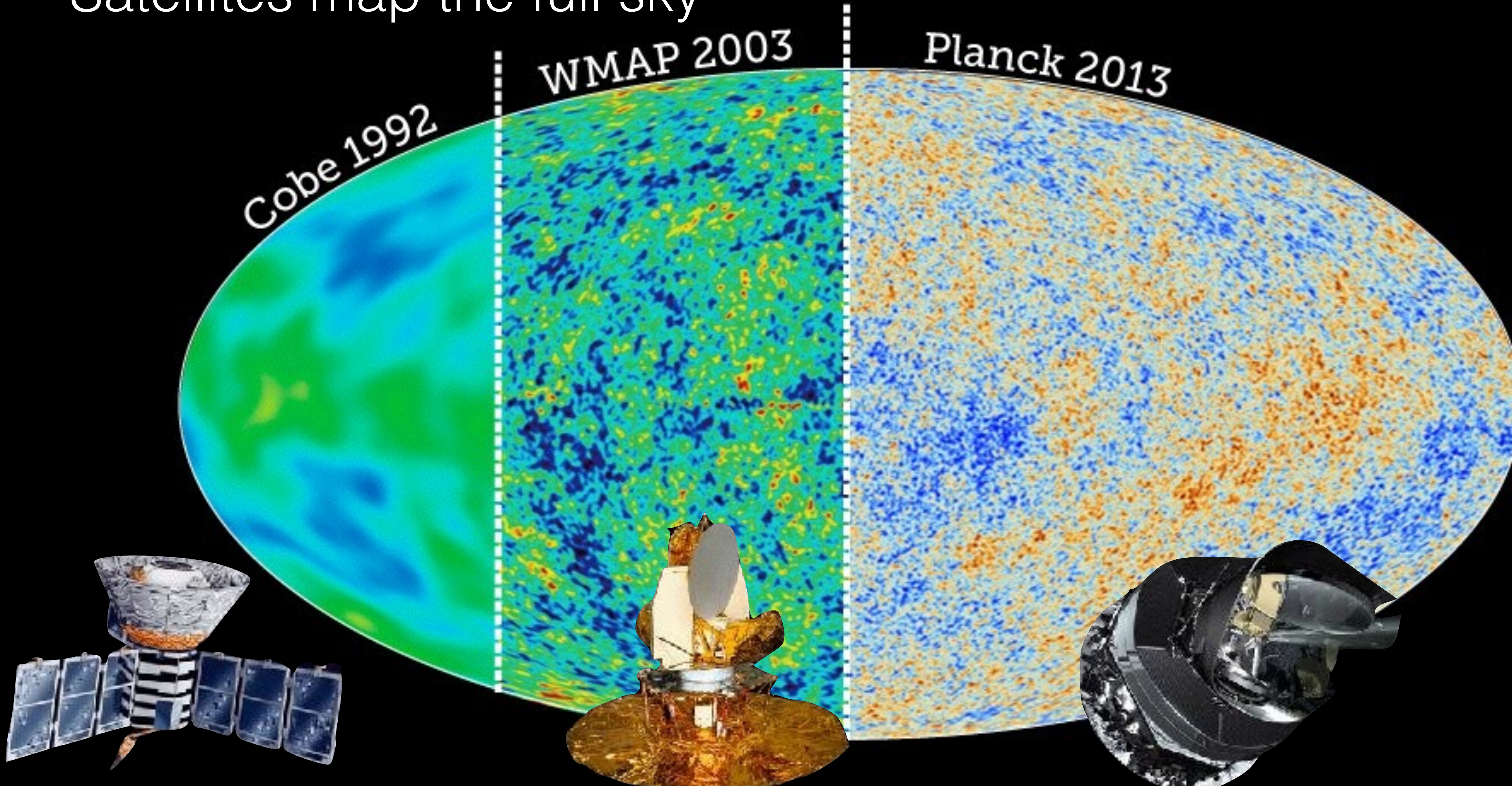
The fluctuations in intensity (anisotropy) trace the fluctuations in the density of the Universe.

$$\frac{\delta I}{I} \propto \frac{\delta\rho}{\rho} \sim 10^{-5}$$

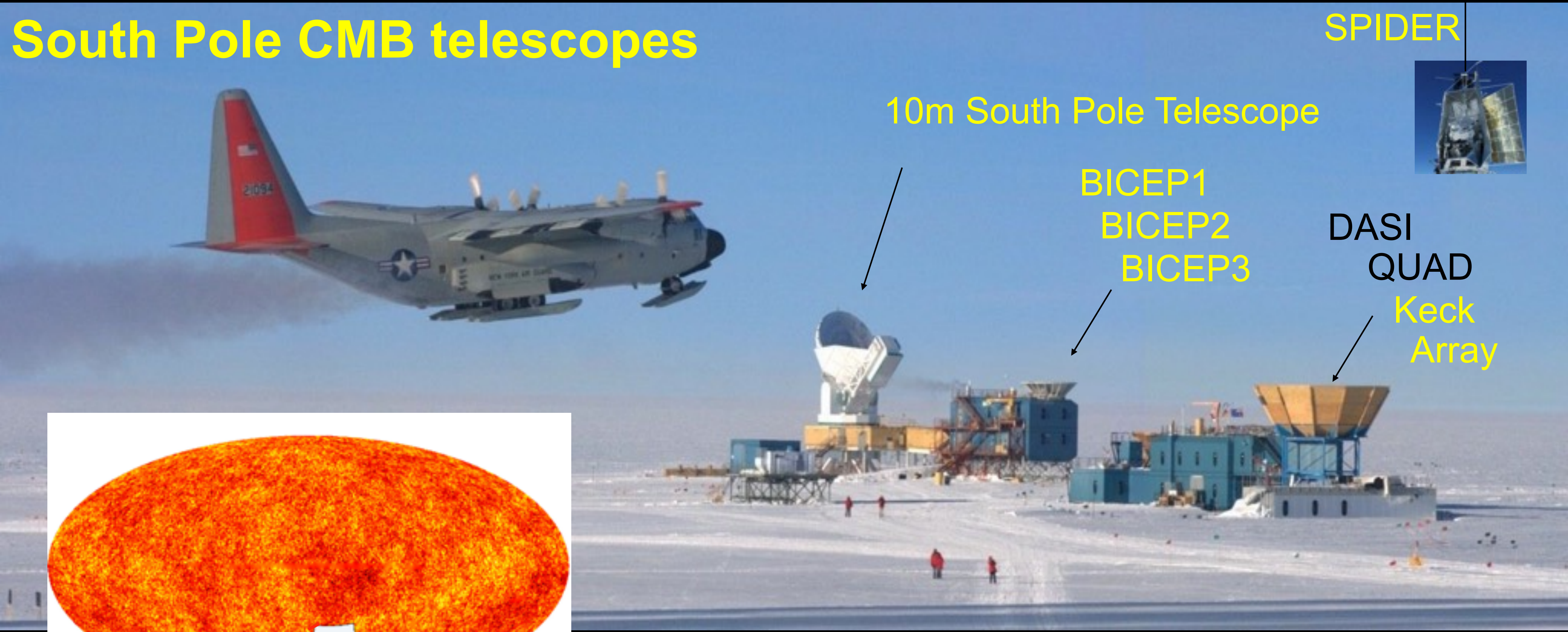


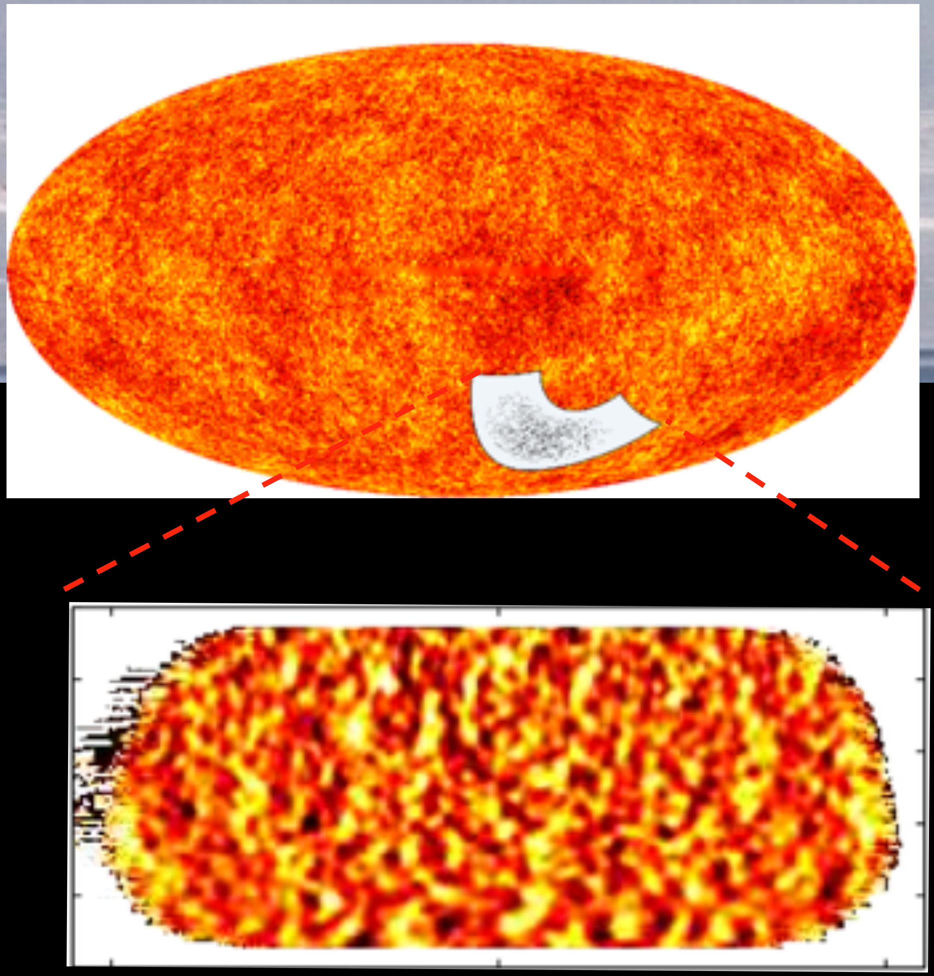
Cosmic Microwave Background

Satellites map the full sky



Cosmic Microwave Background

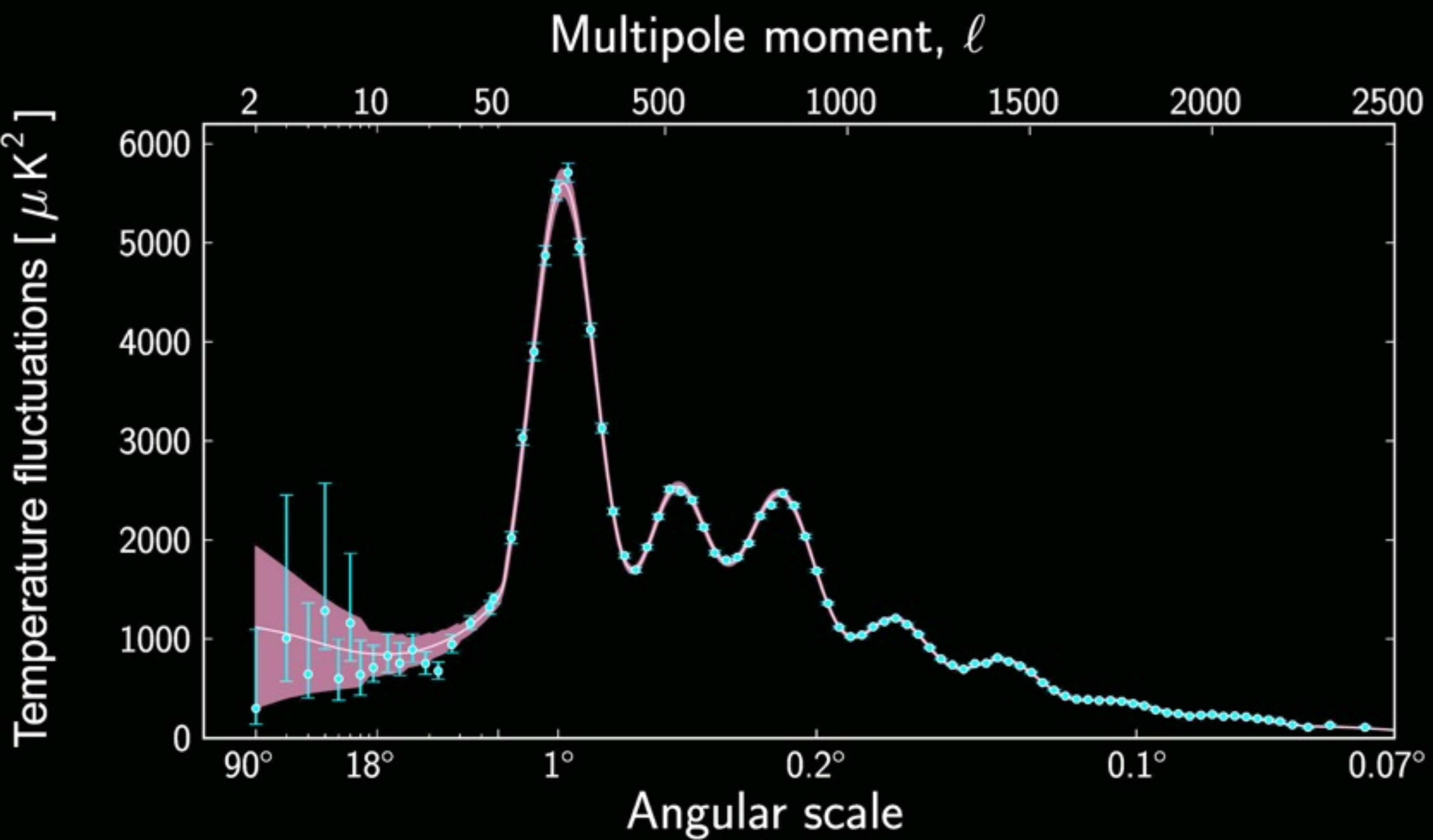




Ground based experiments map part of the sky more deeply

Cosmic Microwave Background

Planck temperature “angular power spectrum”



Planck Collaboration & ESA

Angular Power Spectrum

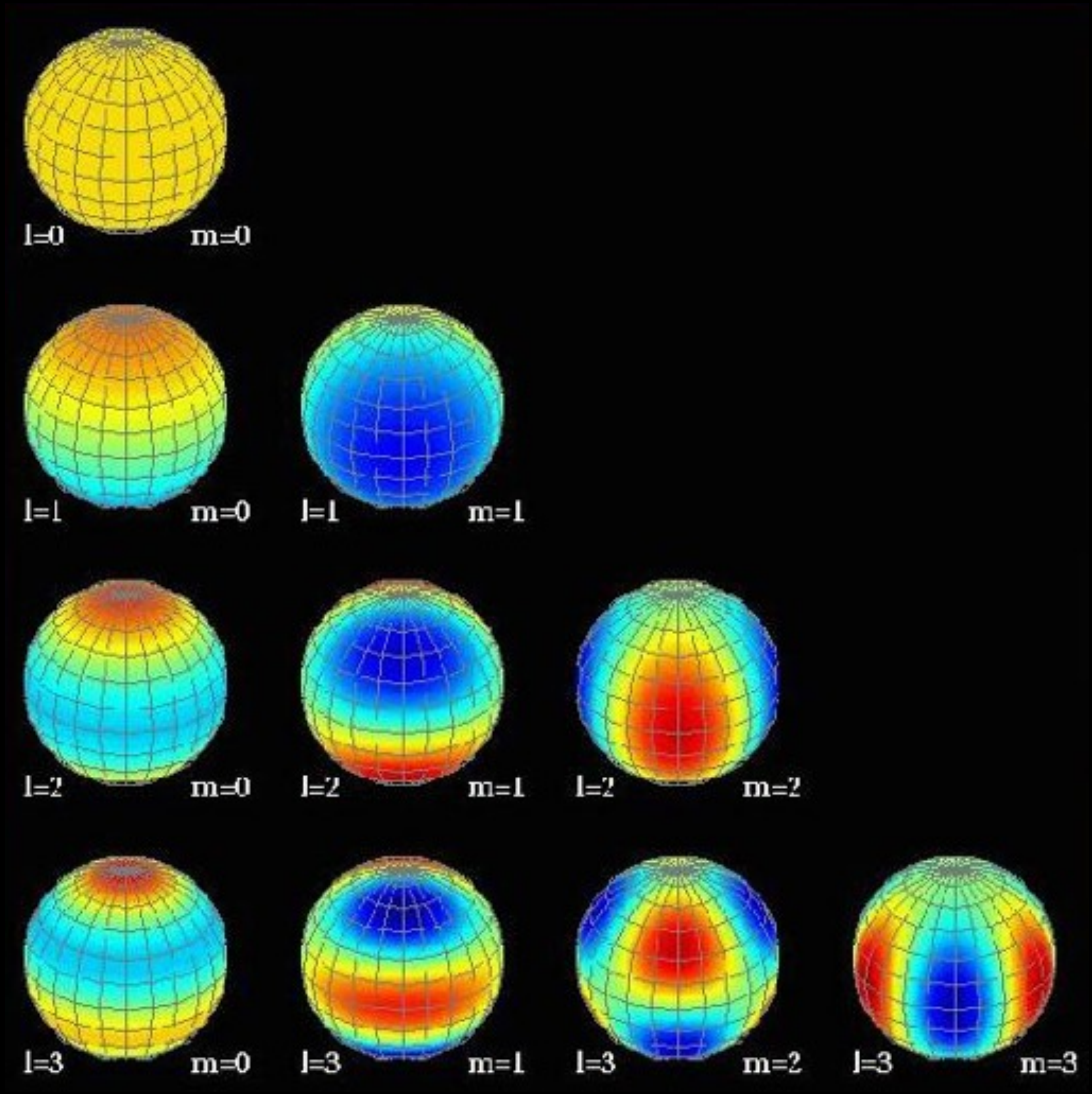
$$T(\theta,\Phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} a_{\ell,m}\, Y_{\ell,m}(\theta,\Phi)$$

$\ell = 0$

$\ell = 1$

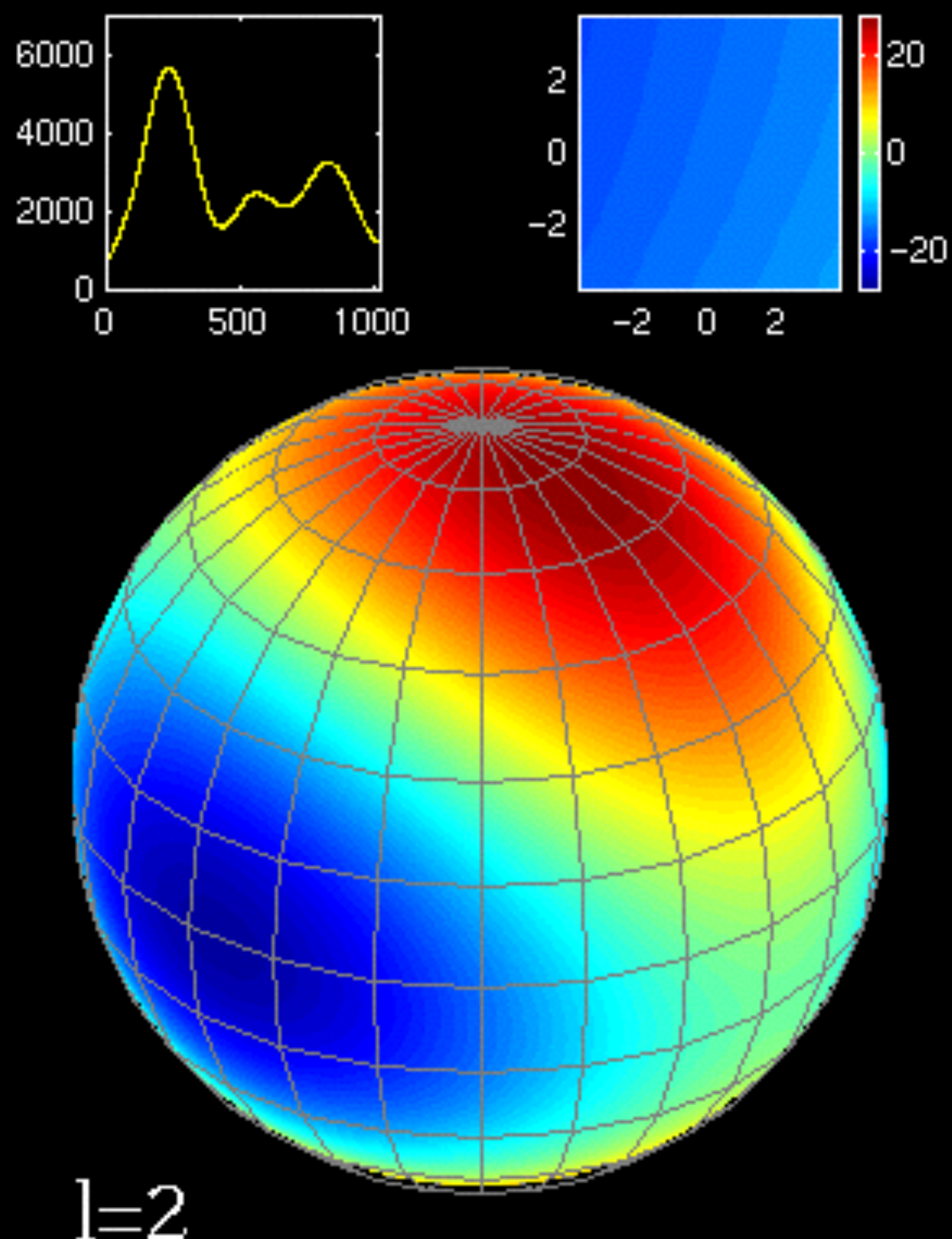
$\ell = 2$

$\ell = 3$



courtesy Clem Pryke

Angular Power Spectrum



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Angular Power Spectrum

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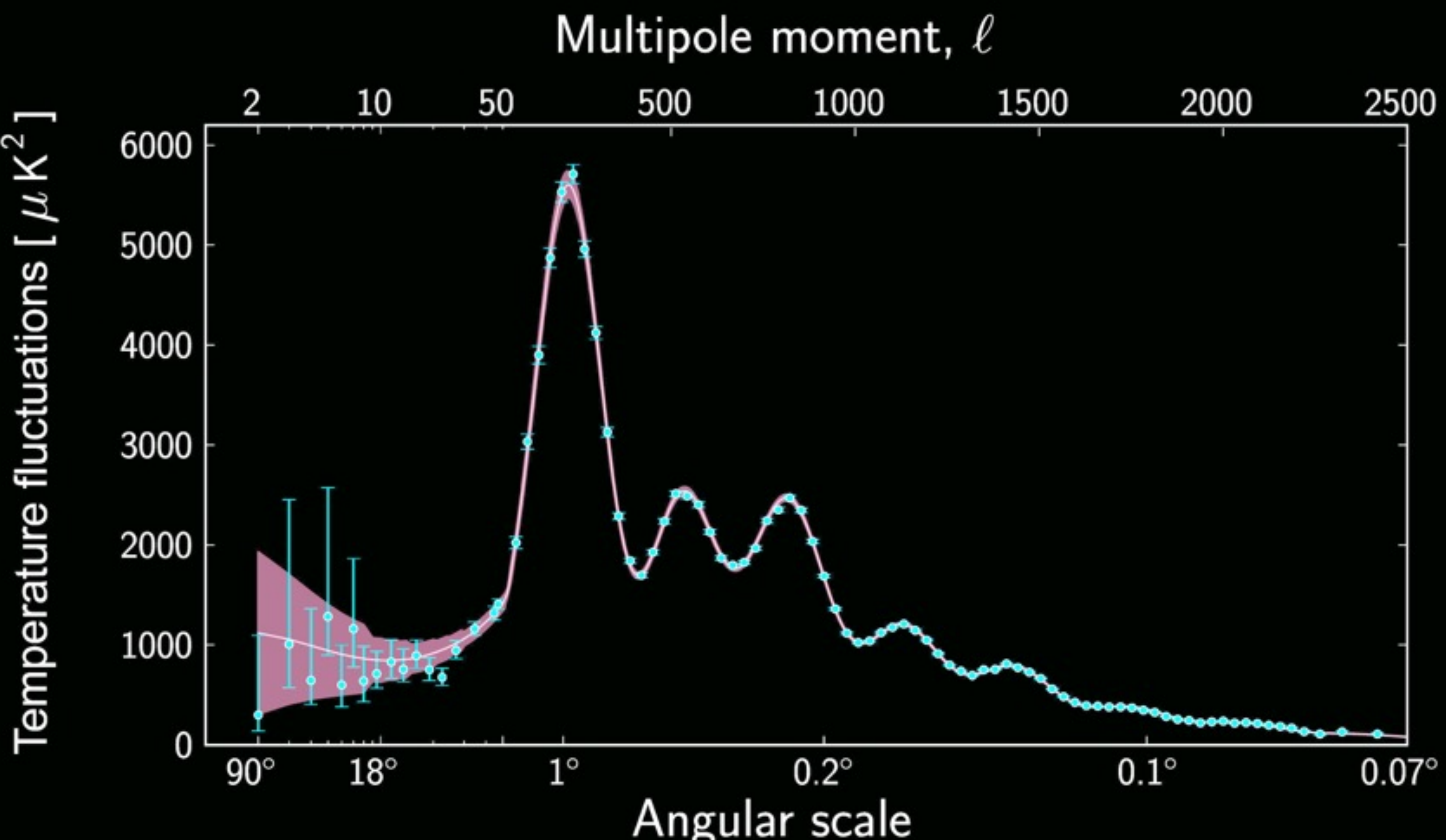

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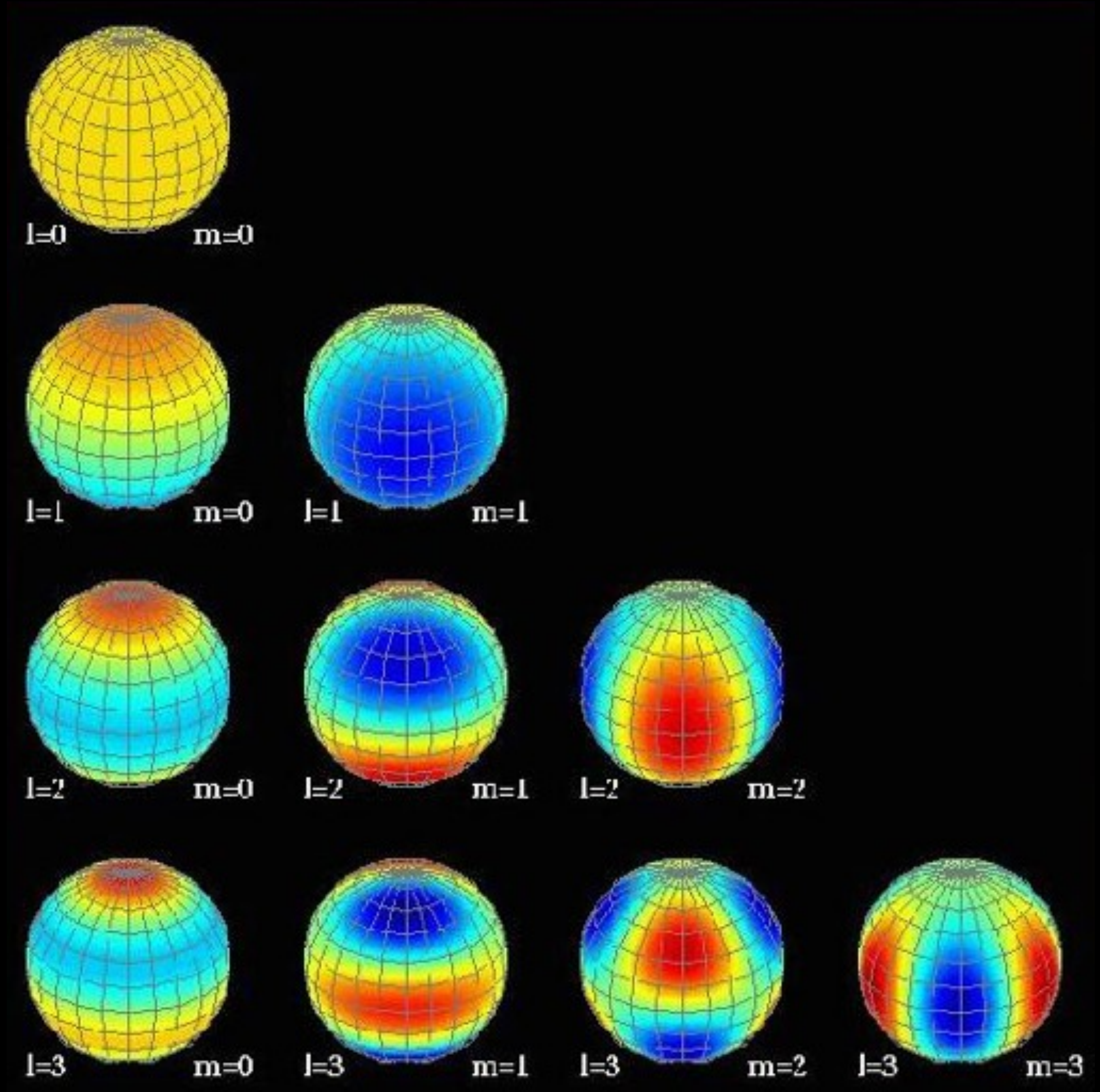

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Angular Power Spectrum

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Angular Power Spectrum

$$T(\theta,\Phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{+\ell} a_{\ell,m} Y_{\ell,m}(\theta,\Phi)$$

Typically, one sees the power spectrum plotted as

$$\mathbf{C_l = \langle a_{lm}^2 \rangle}$$

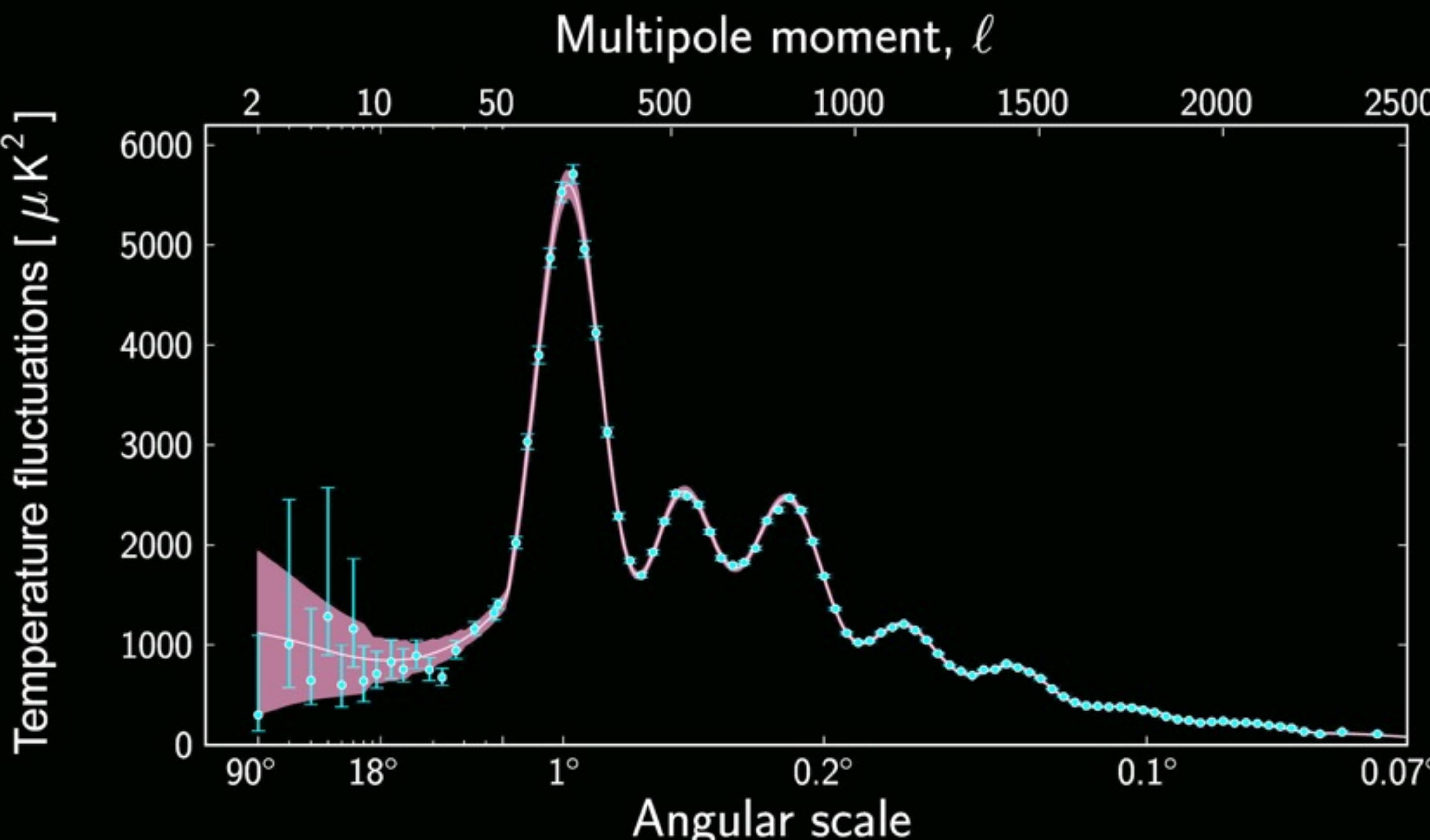
(e.g. the variance of the a_{lm}'s).

Oftentimes this is binned in to l bins and/or multiplied by the factor l(l+1)/2pi.

courtesy Clem Pryke

Angular Power Spectrum

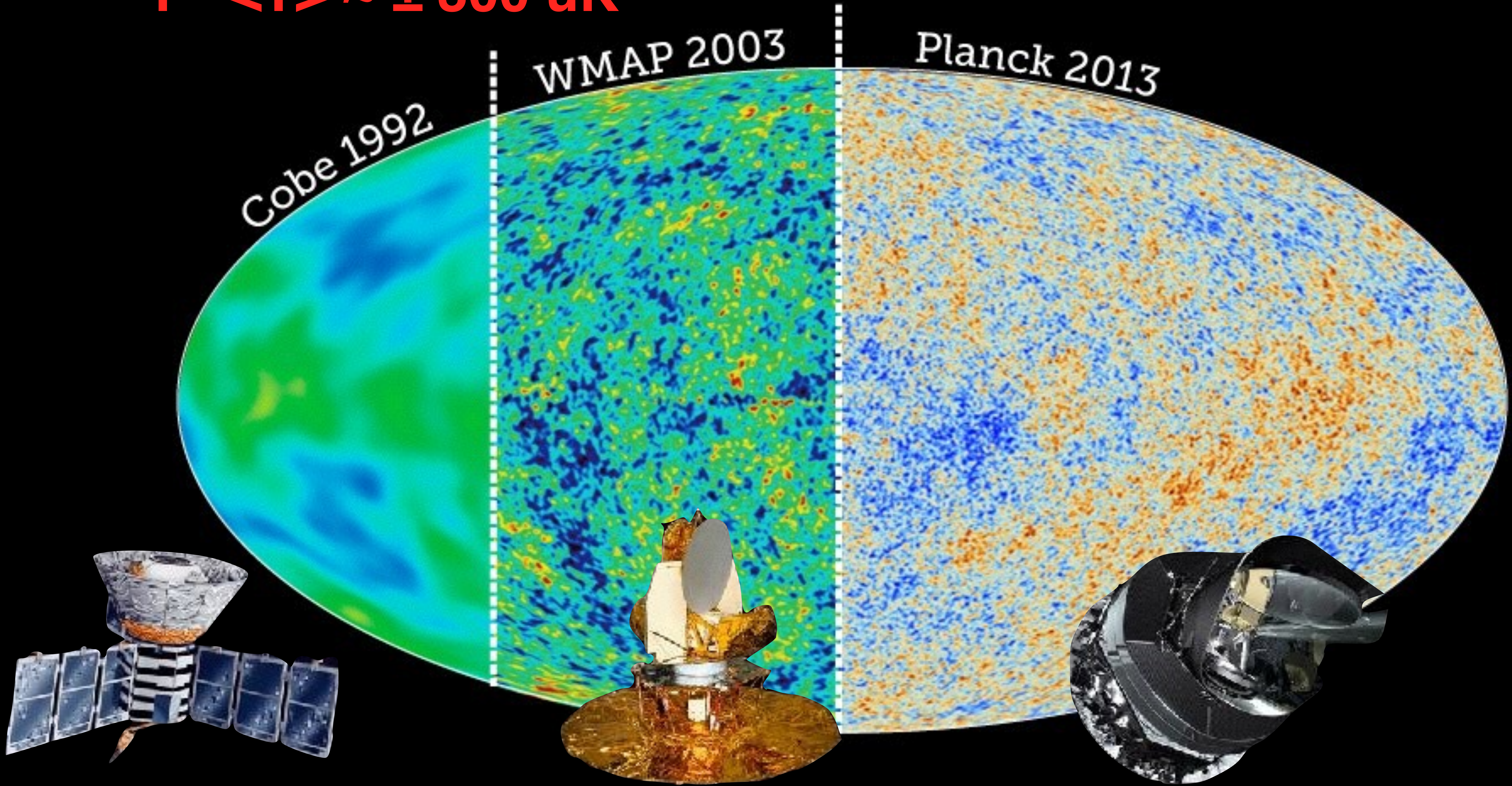
Planck temperature “angular power spectrum”



Planck Collaboration & ESA

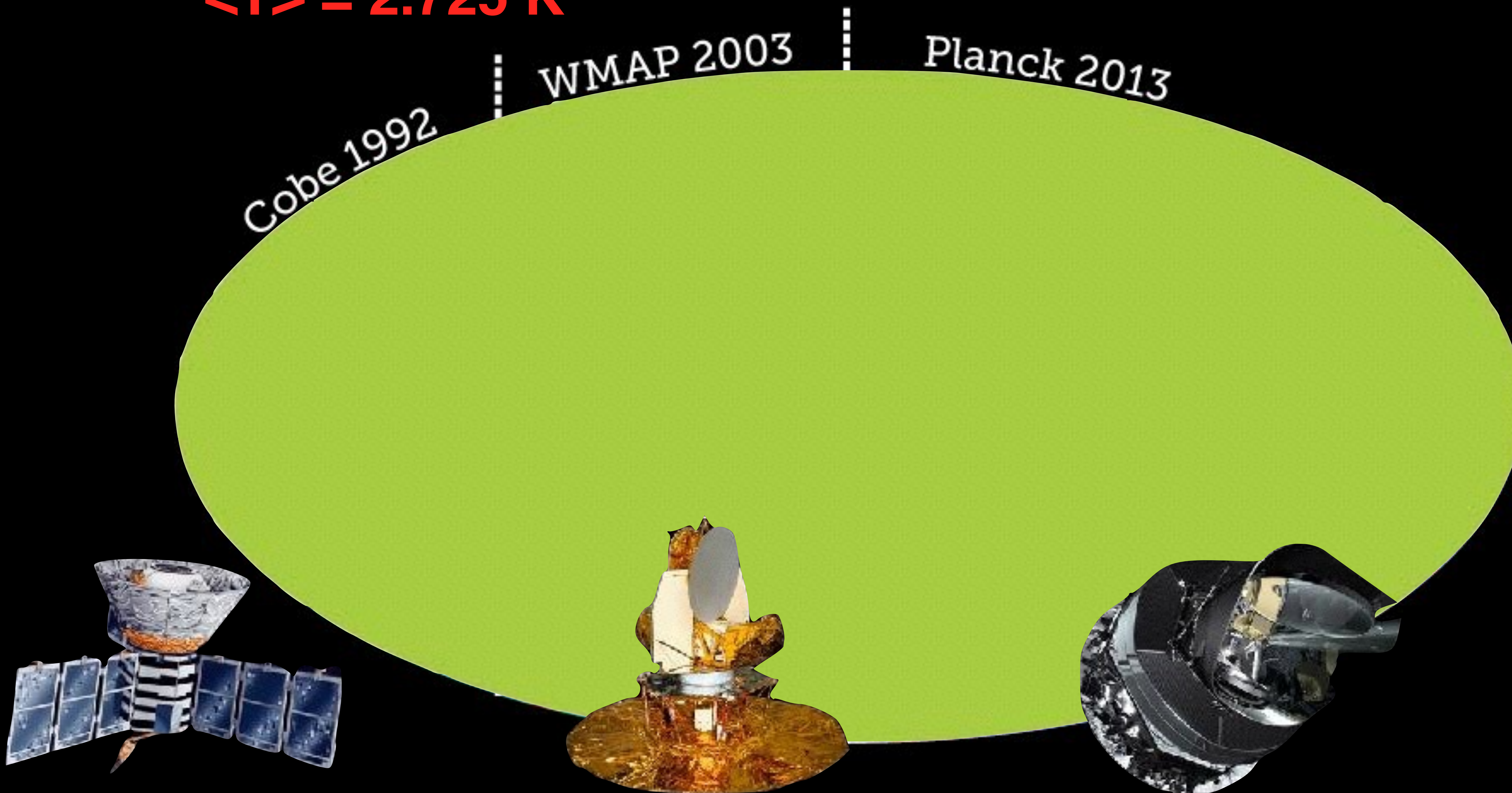
Cosmic Microwave Background

T - <T> ~ ± 300 uK



Cosmic Microwave Background

<T> = 2.725 K



Cosmic Microwave Background

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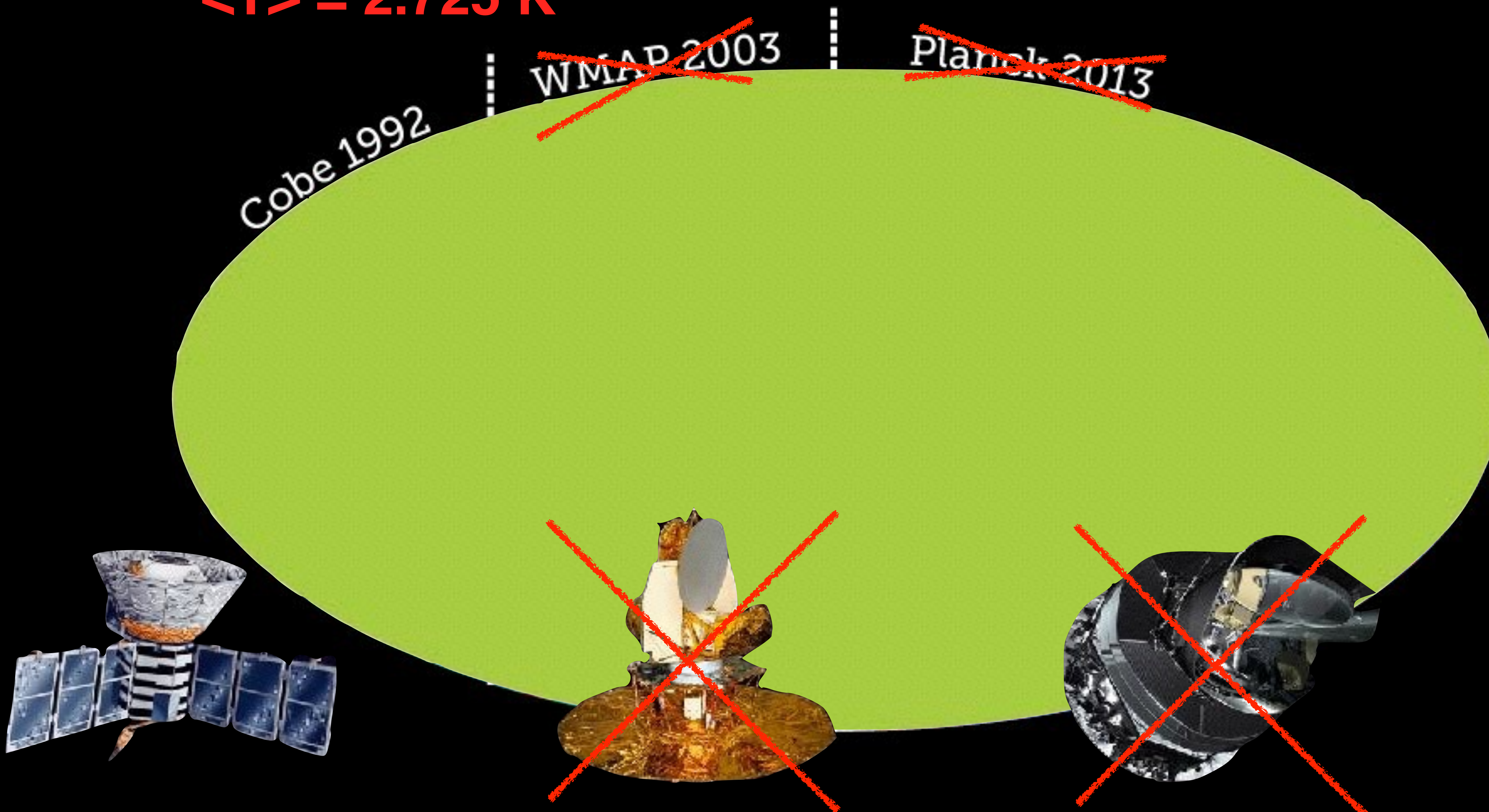
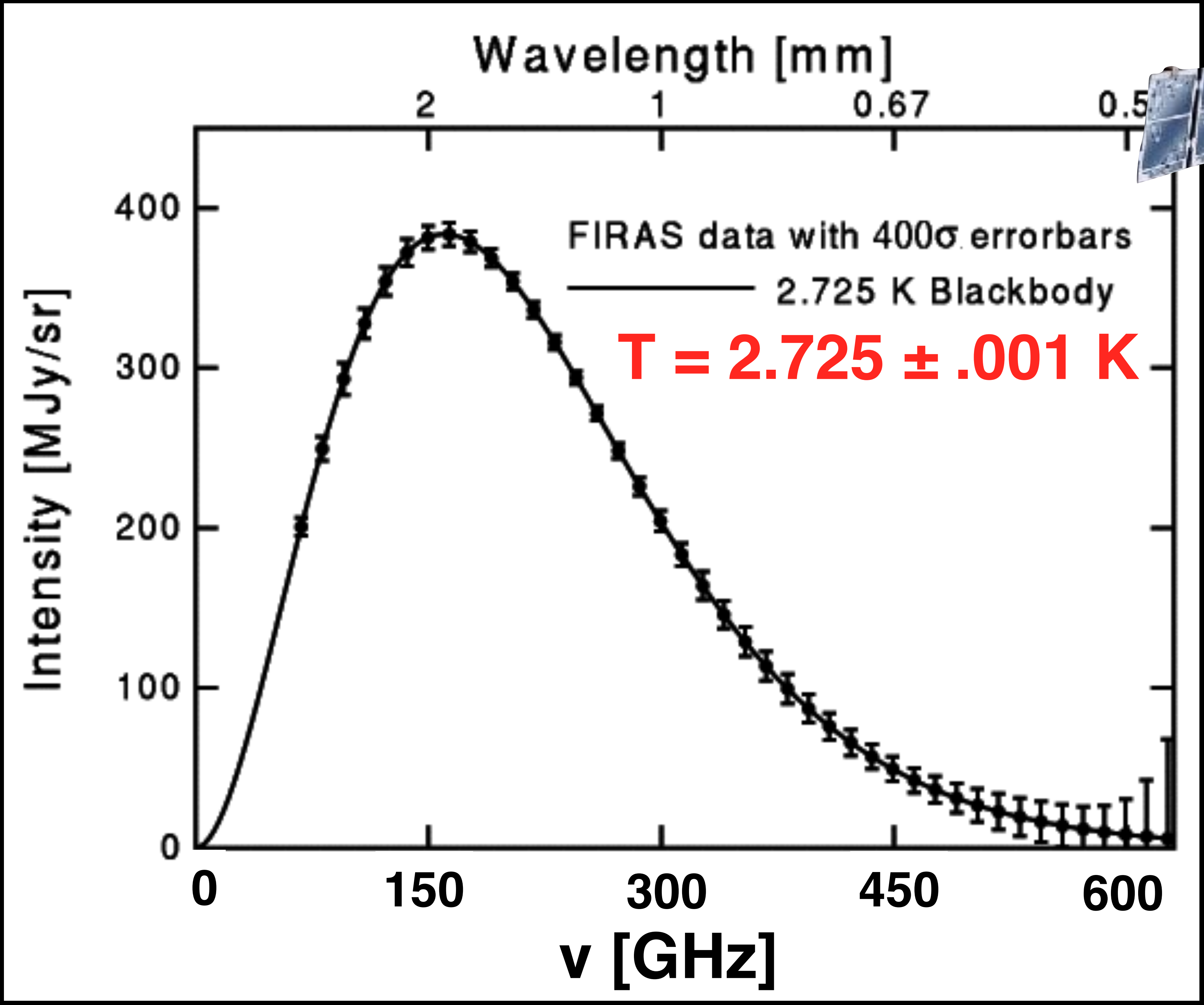


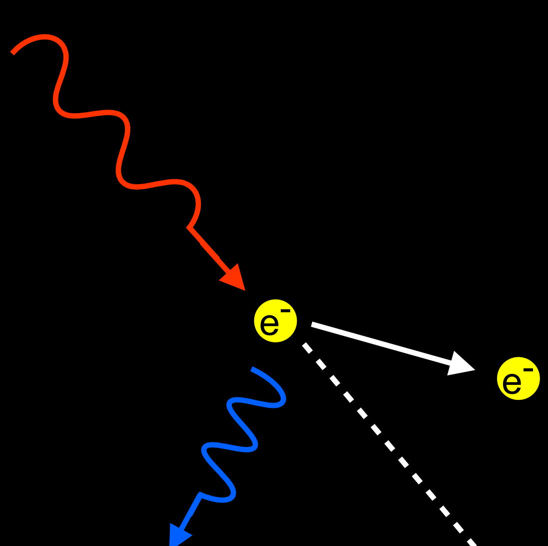
CMB Spectrum



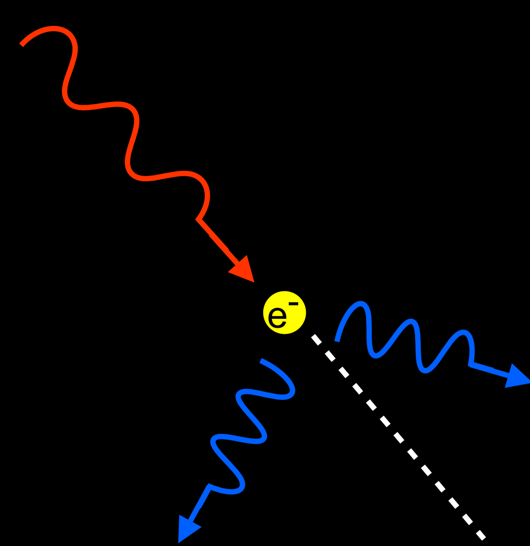
CMB Spectrum

Why should the CMB be a blackbody?

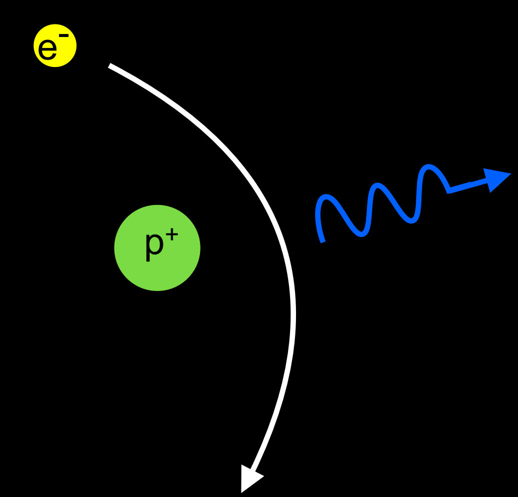
- Imagine some energy is injected into the primordial plasma
- Two things need to happen to “maintain” the blackbody photon spectrum:
  1. photons and baryons are redistributed in energy by Compton scattering
  2. new photons are created by double Compton scattering and Bremsstrahlung



Compton scattering



double Compton



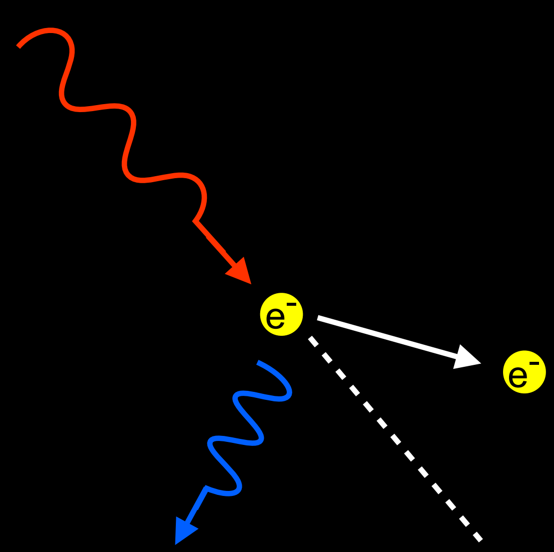
Bremsstrahlung

CMB Spectrum

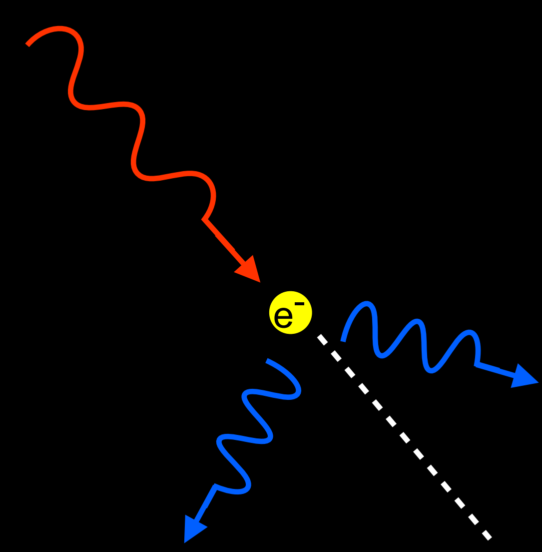
- At **$z > 2 \times 10^6$**, both processes are very efficient and any energy injected into the plasma is quickly thermalized. One parameter, T, is needed to describe the distribution of photons:

$$n(E) = 1 / [e^{E/kT} - 1] \qquad \text{(Planck spectrum)}$$

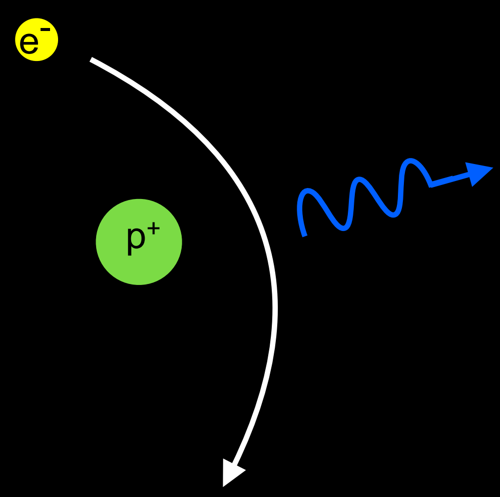
- At **$z < 2 \times 10^6$**, these processes become inefficient and any energy injected in the plasma (particle annihilation, heating, etc.) would not be able to thermalize and a deviation from a blackbody would be observed.



Compton scattering

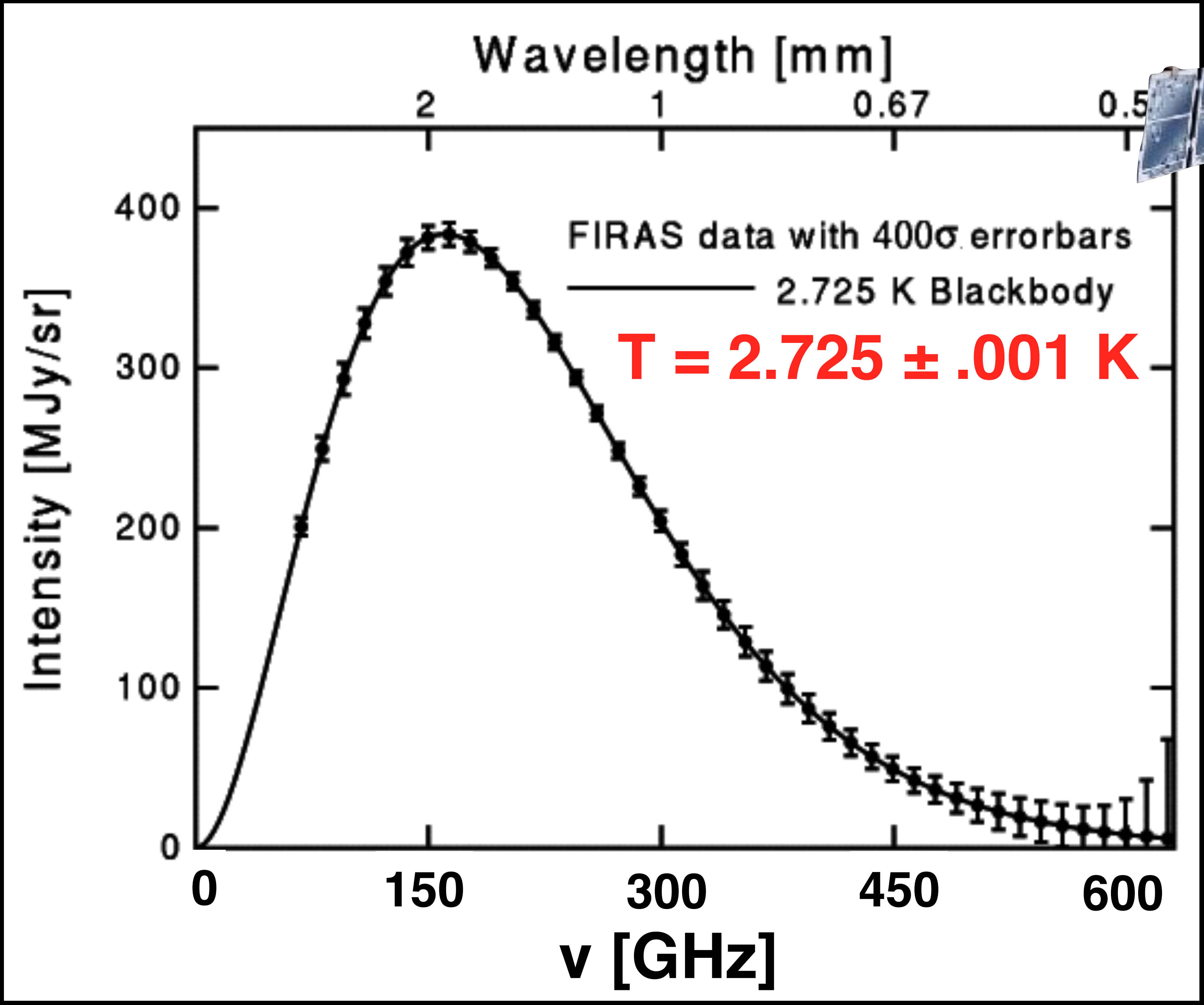


double Compton



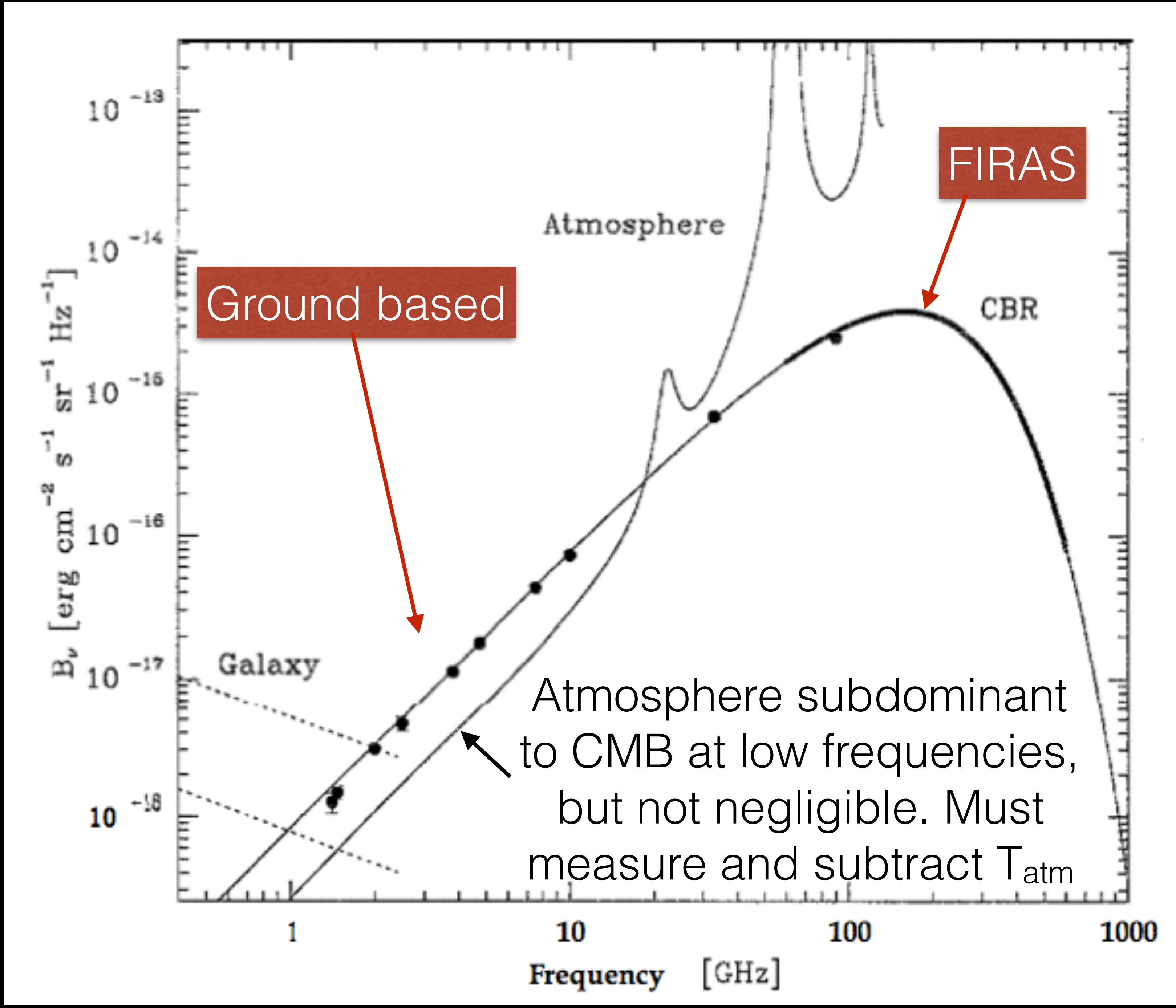
Bremsstrahlung

CMB Spectrum



Ground based CMB spectrum

Even before FIRAS, we knew $T_{CMB} \pm .06$ K from ground based measurements and $\pm .02$ K from balloons



Bersanelli et al. 1995

The CMB spectrum data is 30 years old and has not been improved upon since then! These instruments need very good cryogenic calibrators.

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All the CMB telescopes you hear about now do not measure absolute intensity, they measure the “angular anisotropy” of the CMB.

This includes the ground based and space based missions.

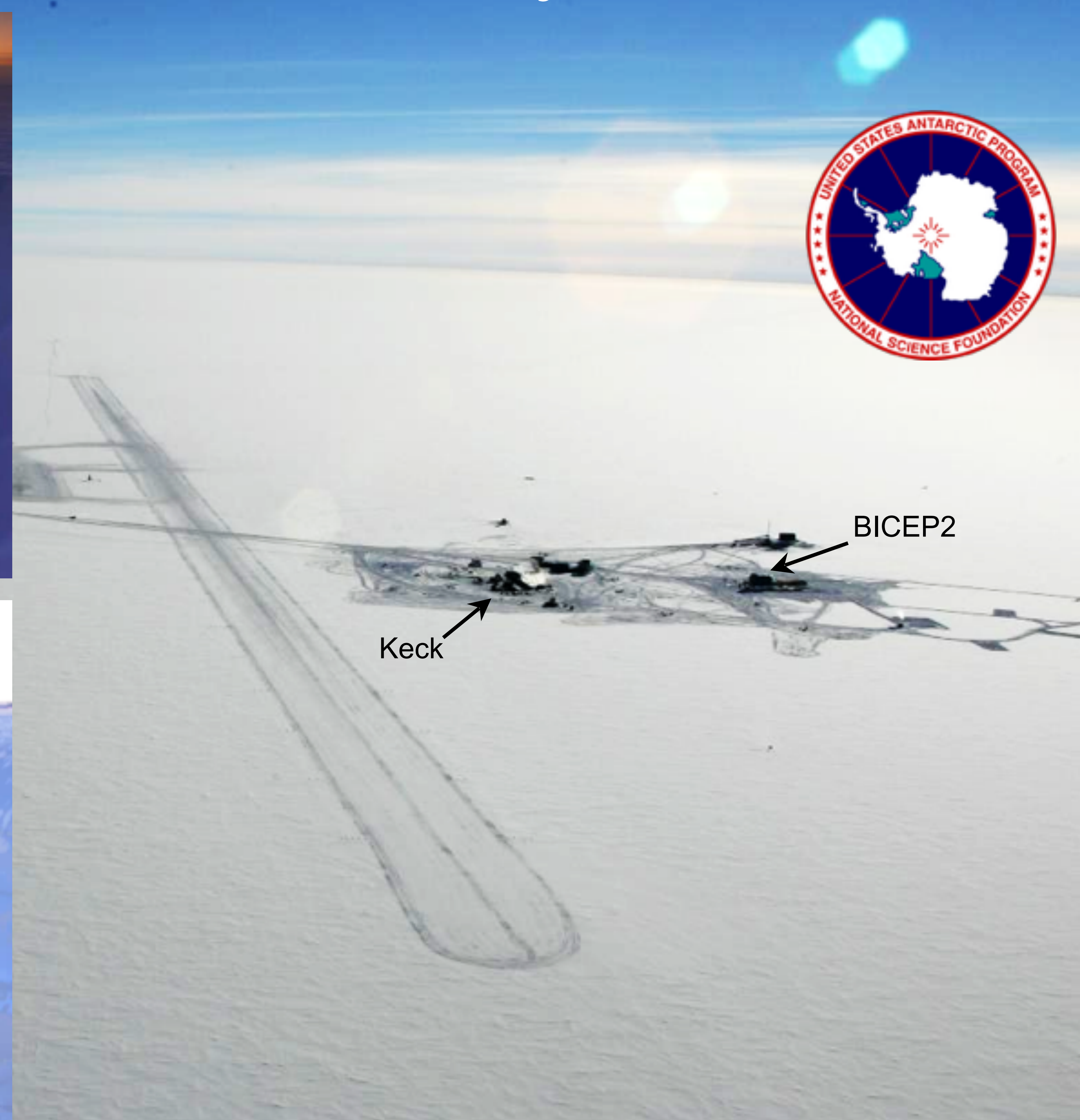
But if you can’t measure T to better than 0.02 K from the ground, how do the ground based telescopes make sub-uK level measurements of the anisotropy?

But if you can't measure T to better than 0.02 K from the ground, how do the ground based telescopes make sub-uK level measurements of the anisotropy?

Answer: don't make absolute intensity measurements, make a differential measurement between two different points on the sky.

BICEP2 and Keck Array

Keck Array 2011-present



South Pole is high (~10,000 ft) and dry and has a very stable atmosphere during the 6 month long night.

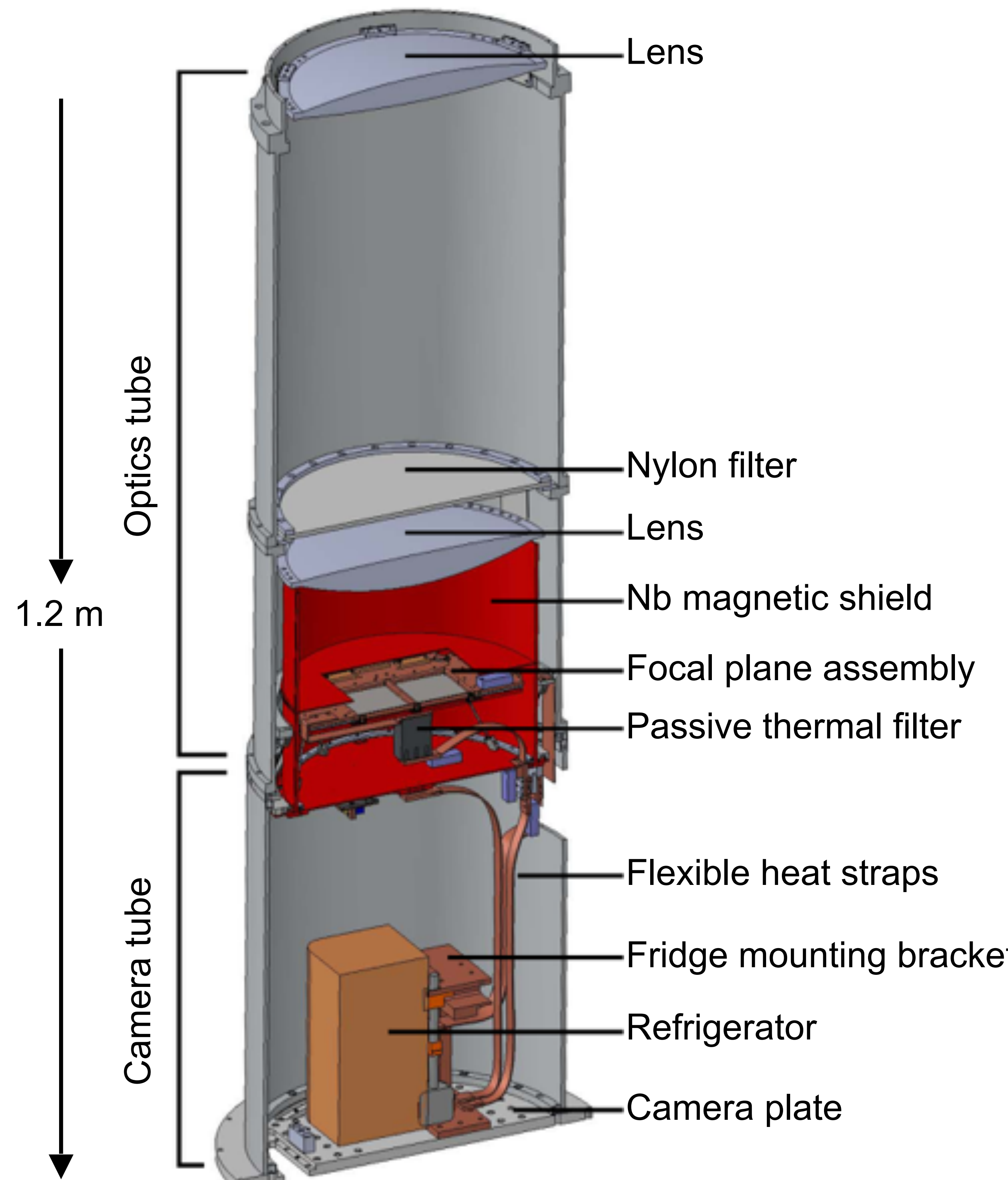
The BICEP2/Keck Telescopes

Telescope as compact as possible while still having the angular resolution to observe degree-scale features.

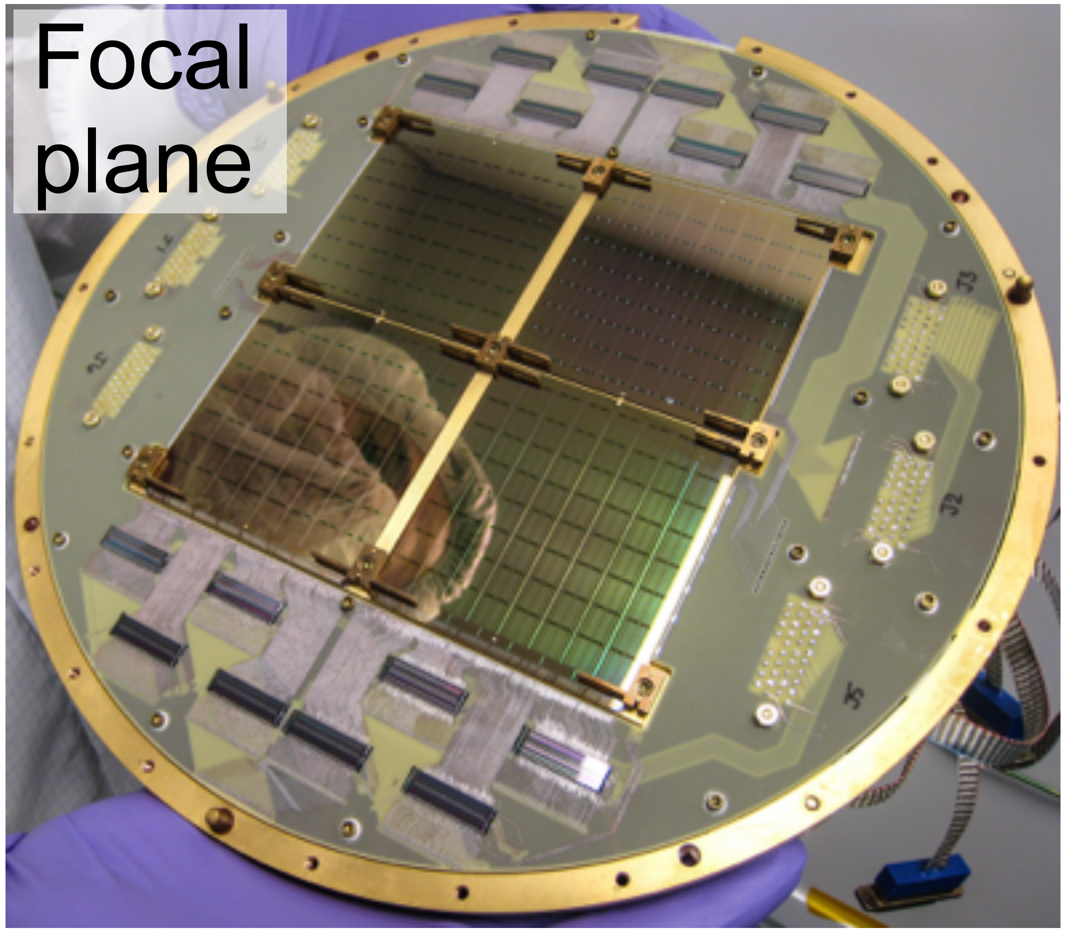
On-axis, refractive optics allow the entire telescope to rotate around boresight for polarization modulation.

Liquid helium cools the optical elements to 4.2 K.

A 3-stage helium sorption refrigerator further cools the detectors to 0.27 K.



Mass-produced Superconducting Detectors



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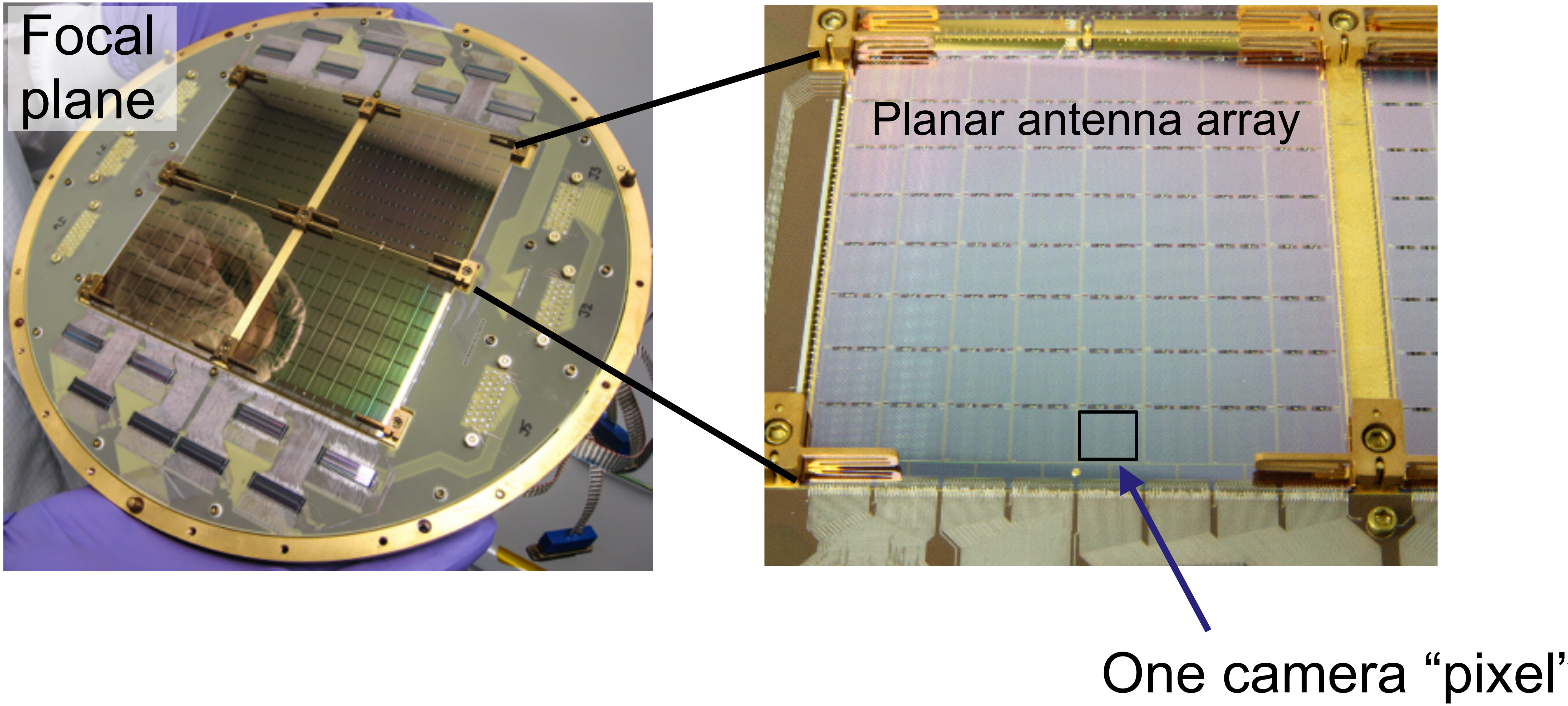

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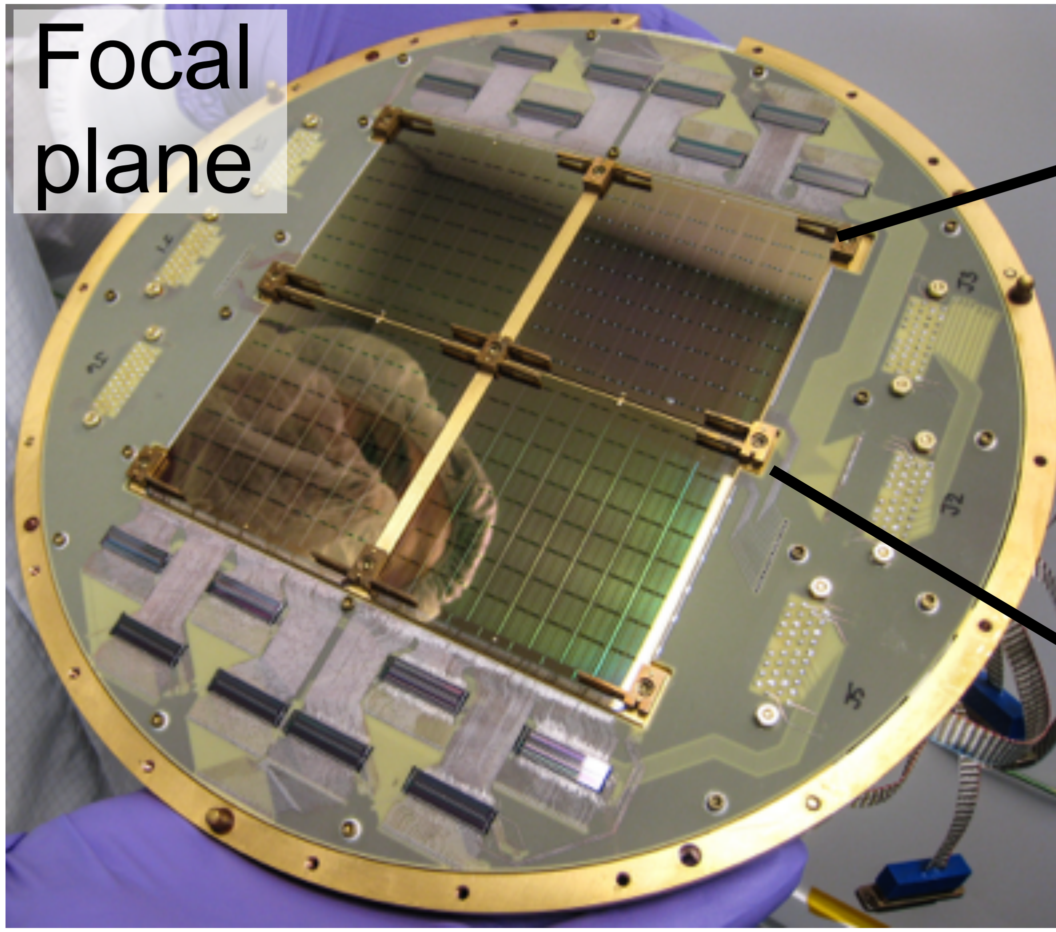
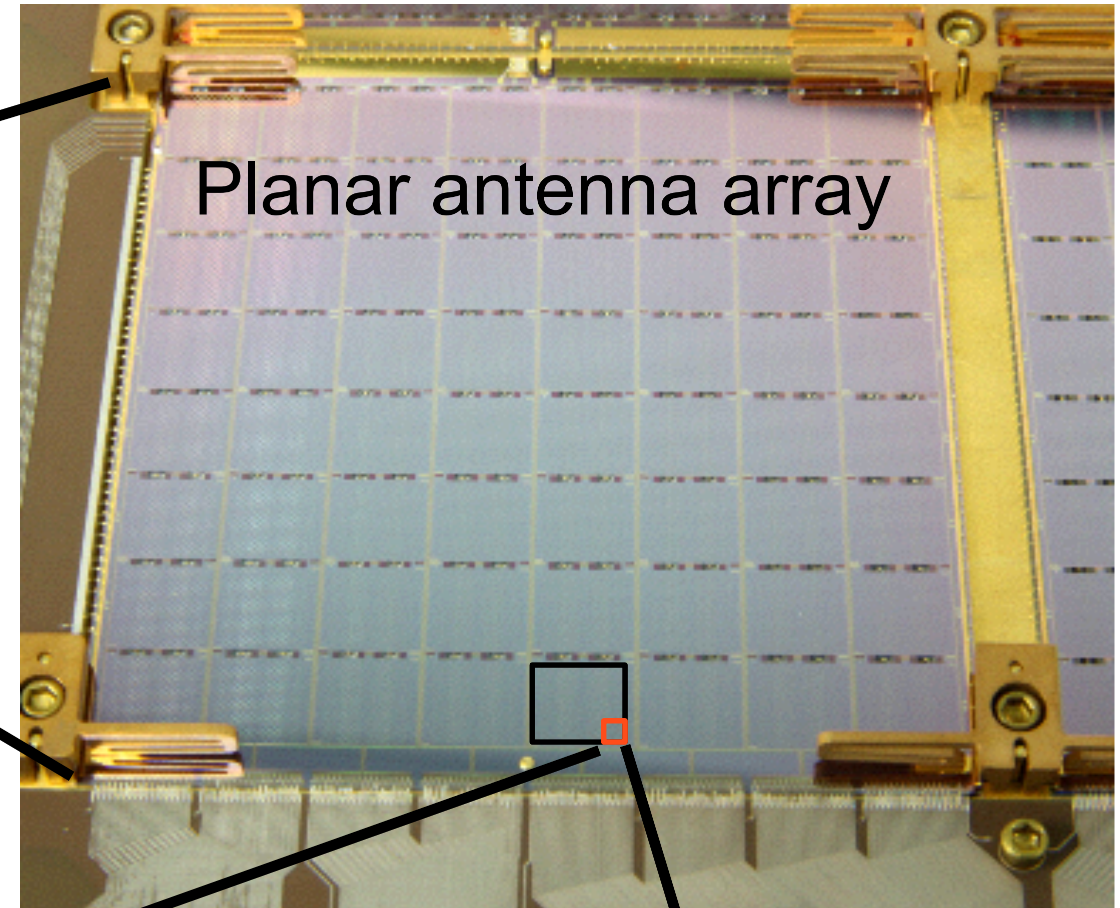
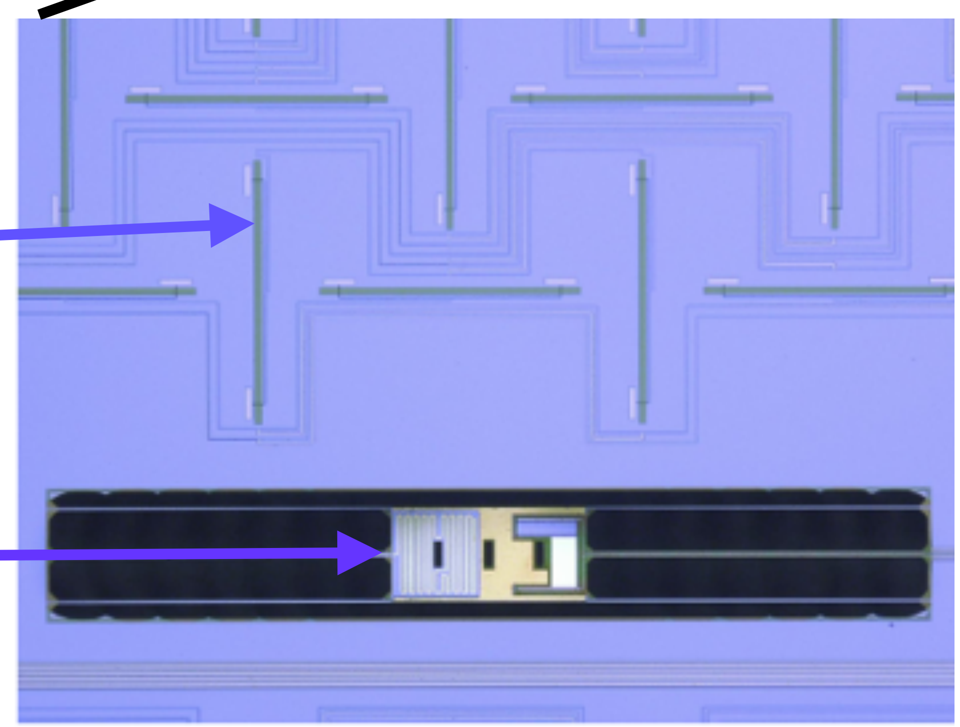
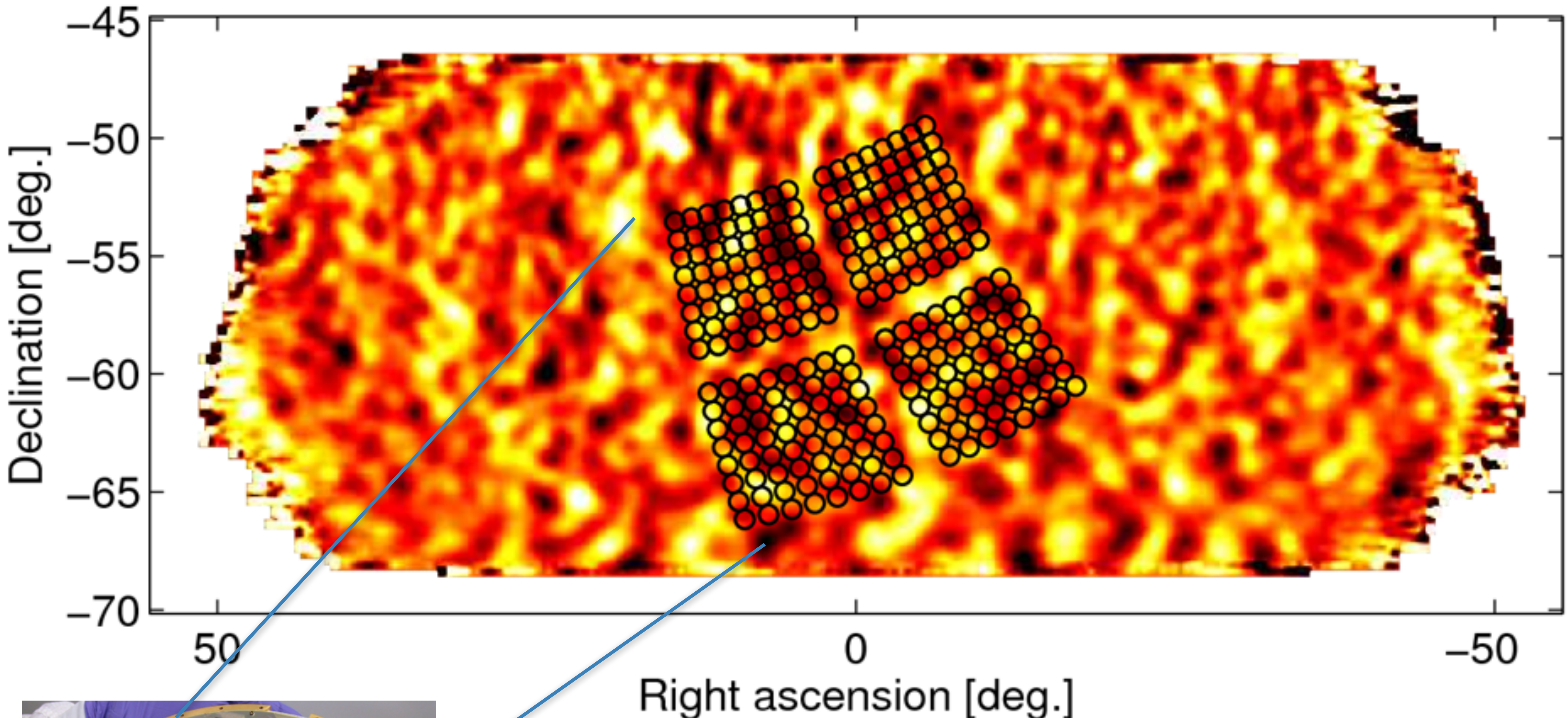
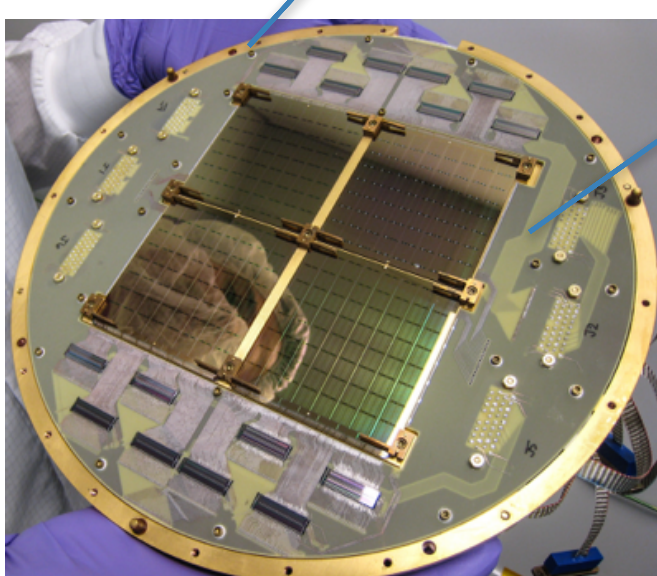






BICEP2 and Keck Array on the Sky





Projection of a single BICEP2/Keck focal plane on the sky!

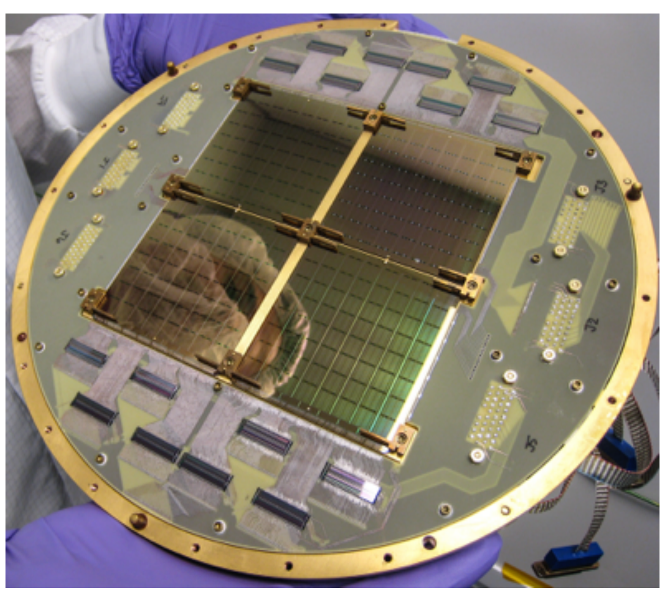
(Background is the CMB temperature map as measured with BICEP2)

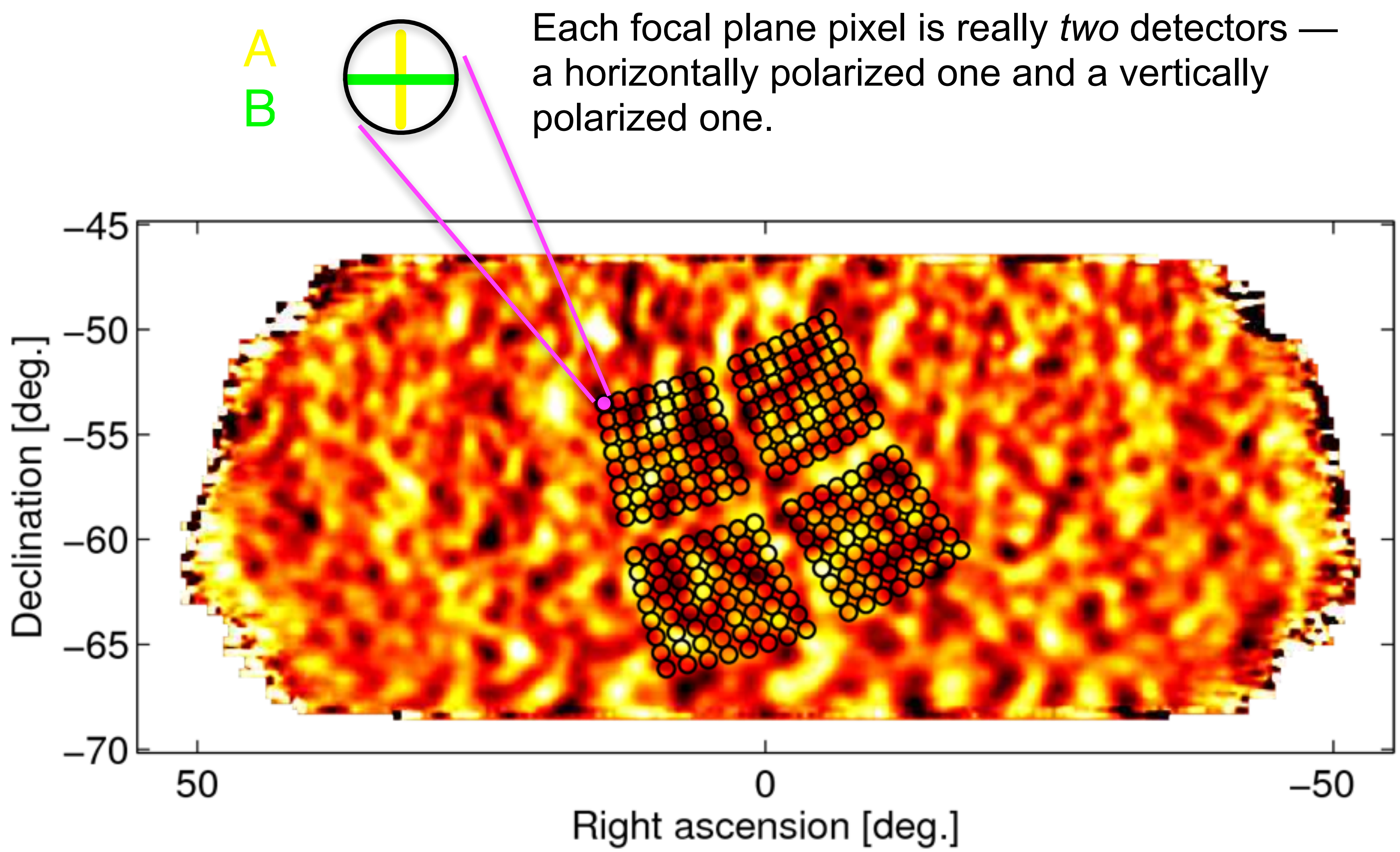
Christopher Sheehy for the BICEP/Keck Collaboration

BICEP2 and Keck Array on the Sky

Measure CMB T by summing the signal from orthogonally polarized detector pairs.

Measure CMB polarization by differencing the signal.



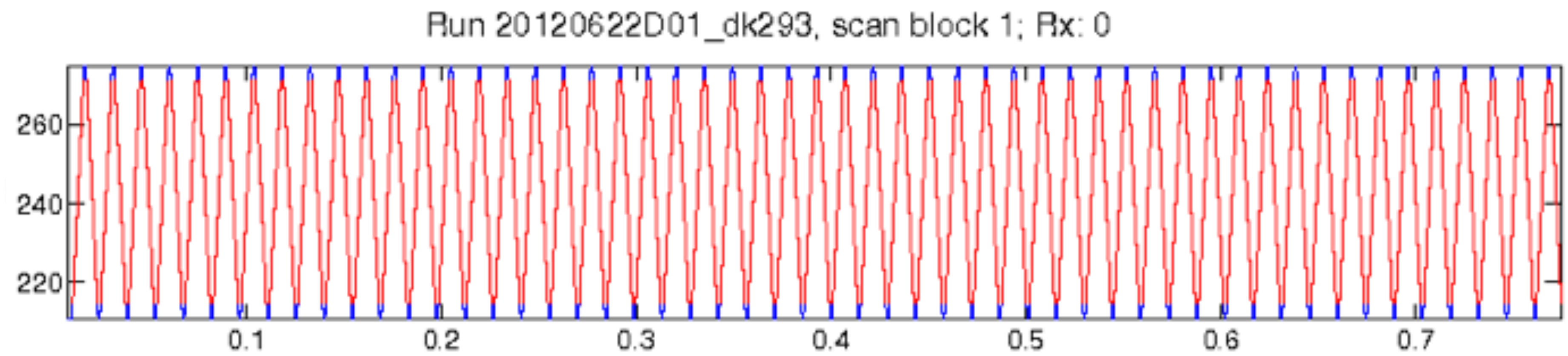


Christopher Sheehy for the Bicep2 Collaboration

video: Robert Schwartz

Raw Data

Telescope Movement

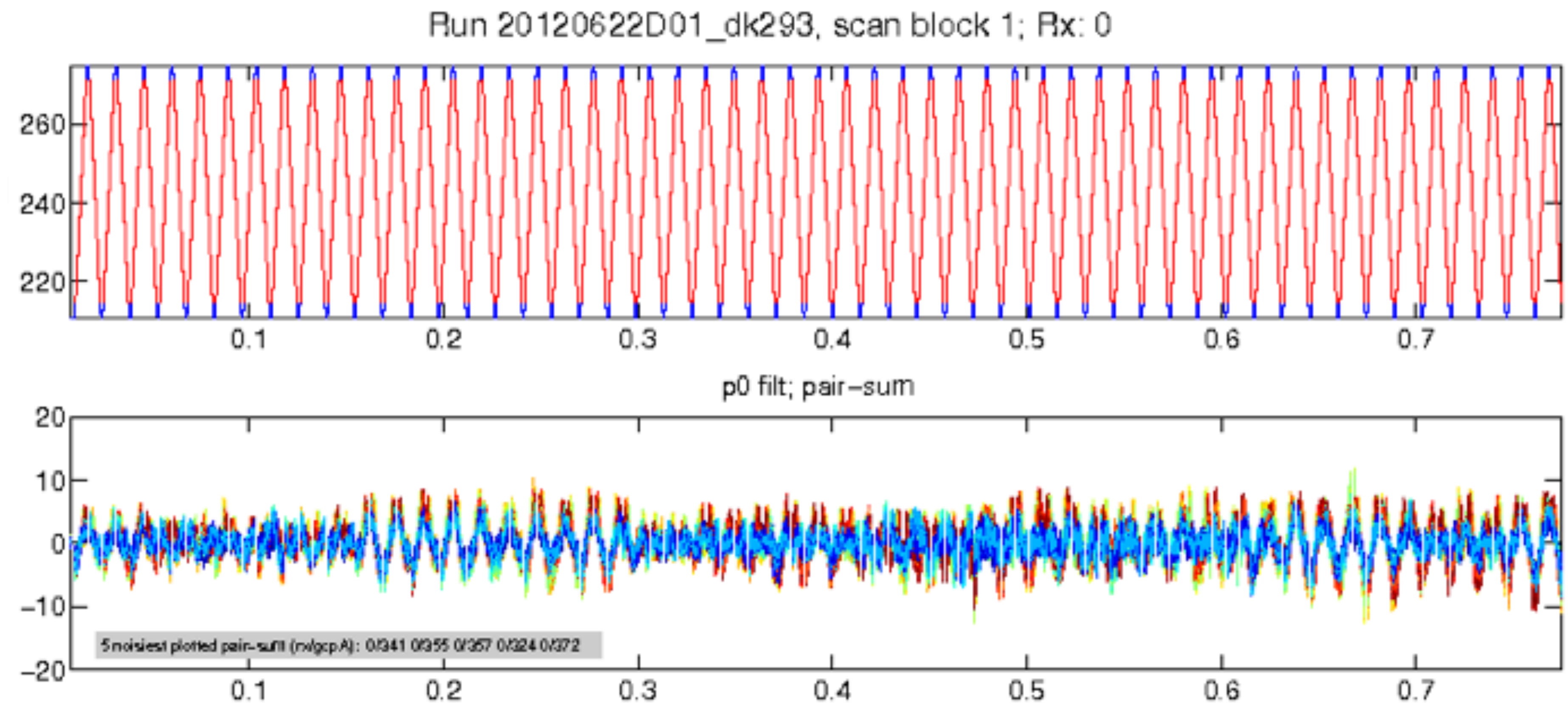


time (~1 hour)

Raw Data

Telescope Movement

Sum of detector pairs



time (~1 hour)

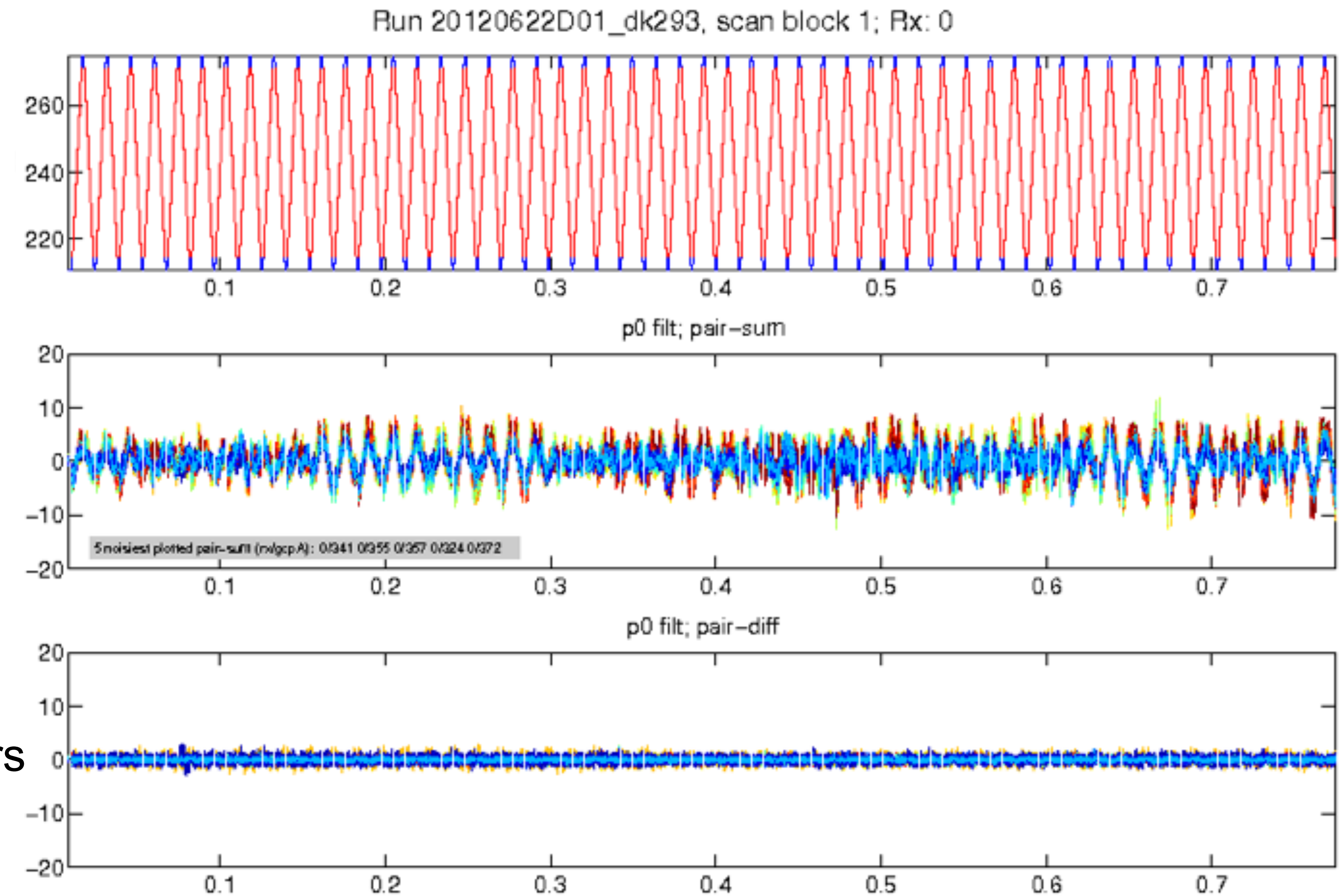
Christopher Sheehy for the Bicep2 Collaboration

Raw Data

Telescope Movement

Sum of detector pairs

Difference of detector pairs



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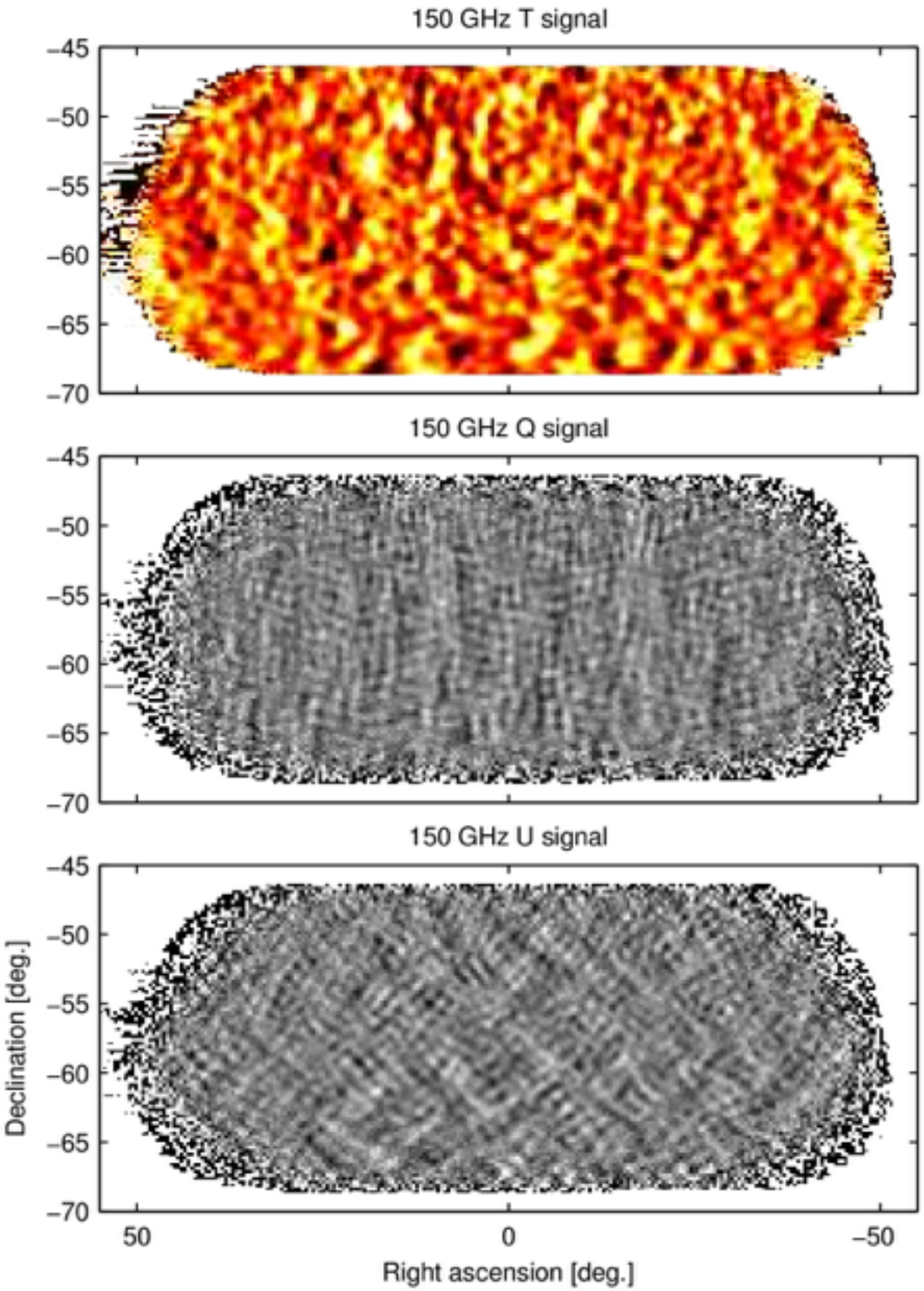
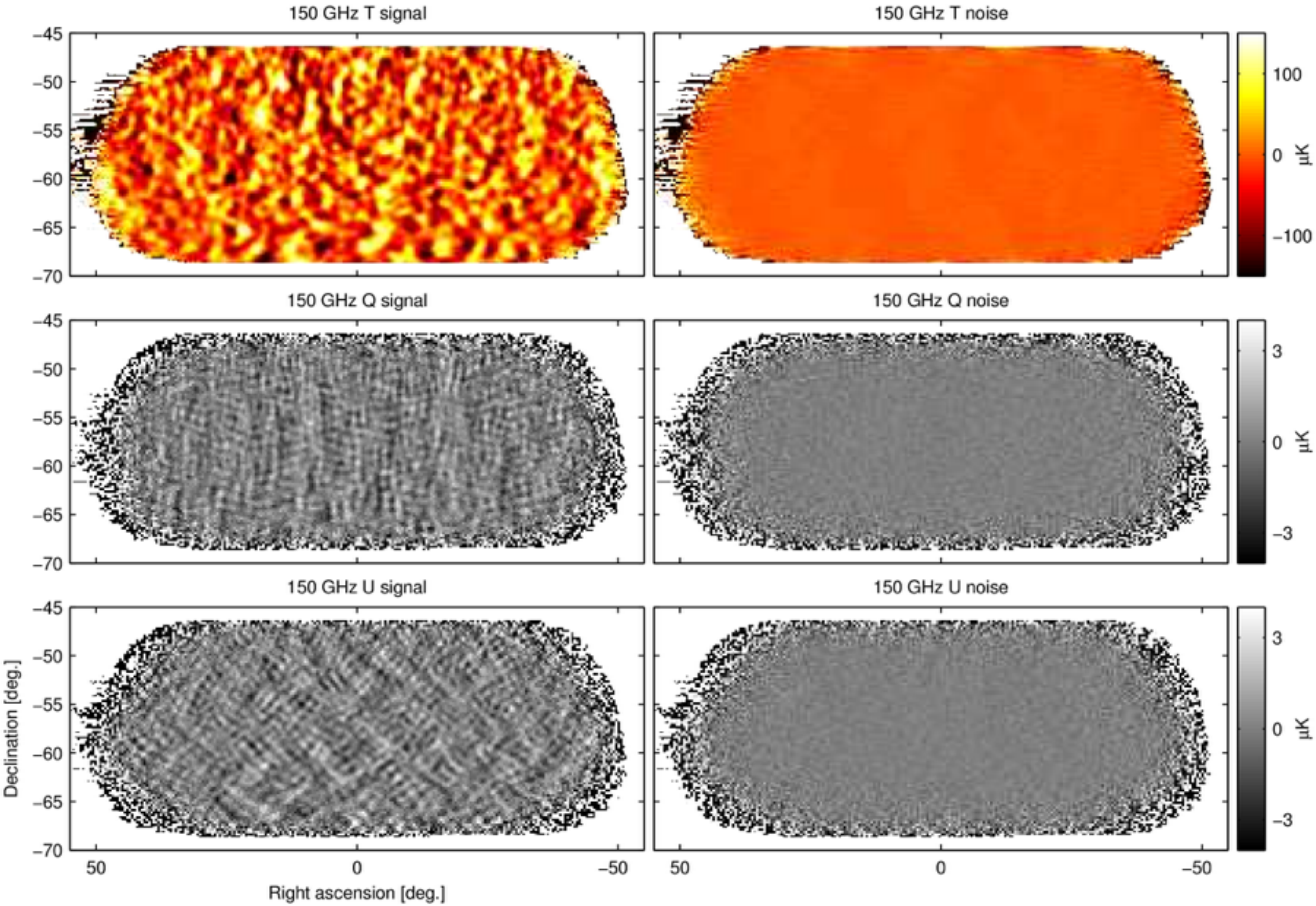
Christopher Sheehy for the Bicep2 Collaboration

150 GHz maps



The BICEP/Keck Collaboration

150 GHz maps



The BICEP/Keck Collaboration

Let’s turn these maps into a power spectrum

courtesy Clem Pryke

Flat sky approximation!

Forget about the fact the sky is curved! Just make a map projection and proceed with Fourier transforms.

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spherical harmonic transform -> Fourier transform

Y_{lm}'s -> sines and cosines

a_{lm}'s -> Fourier coefficients

Flat sky approximation!

Conceptually, Fourier analysis gives us all the intuition we need about the analysis of “full sky”, spherical maps.

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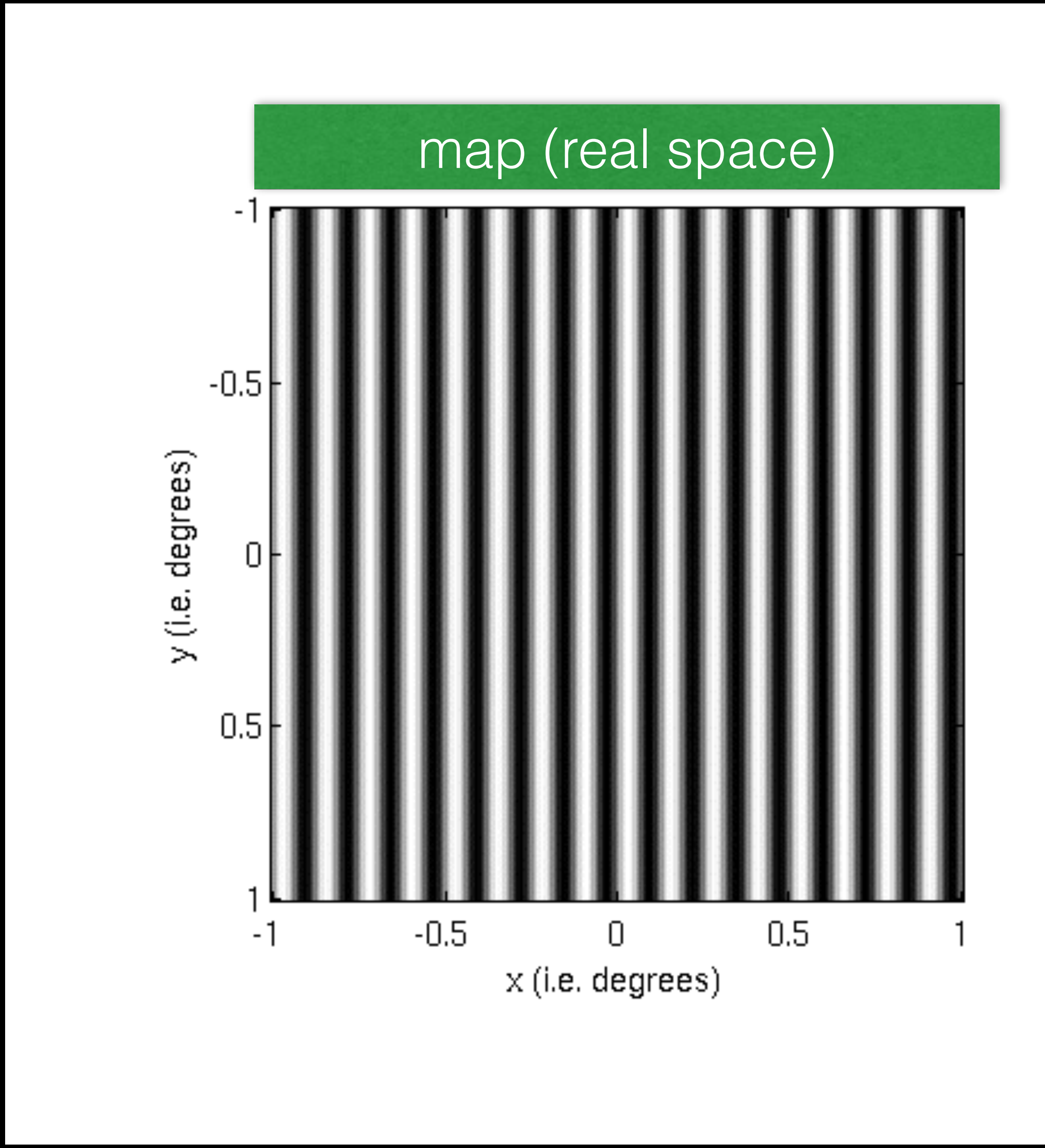
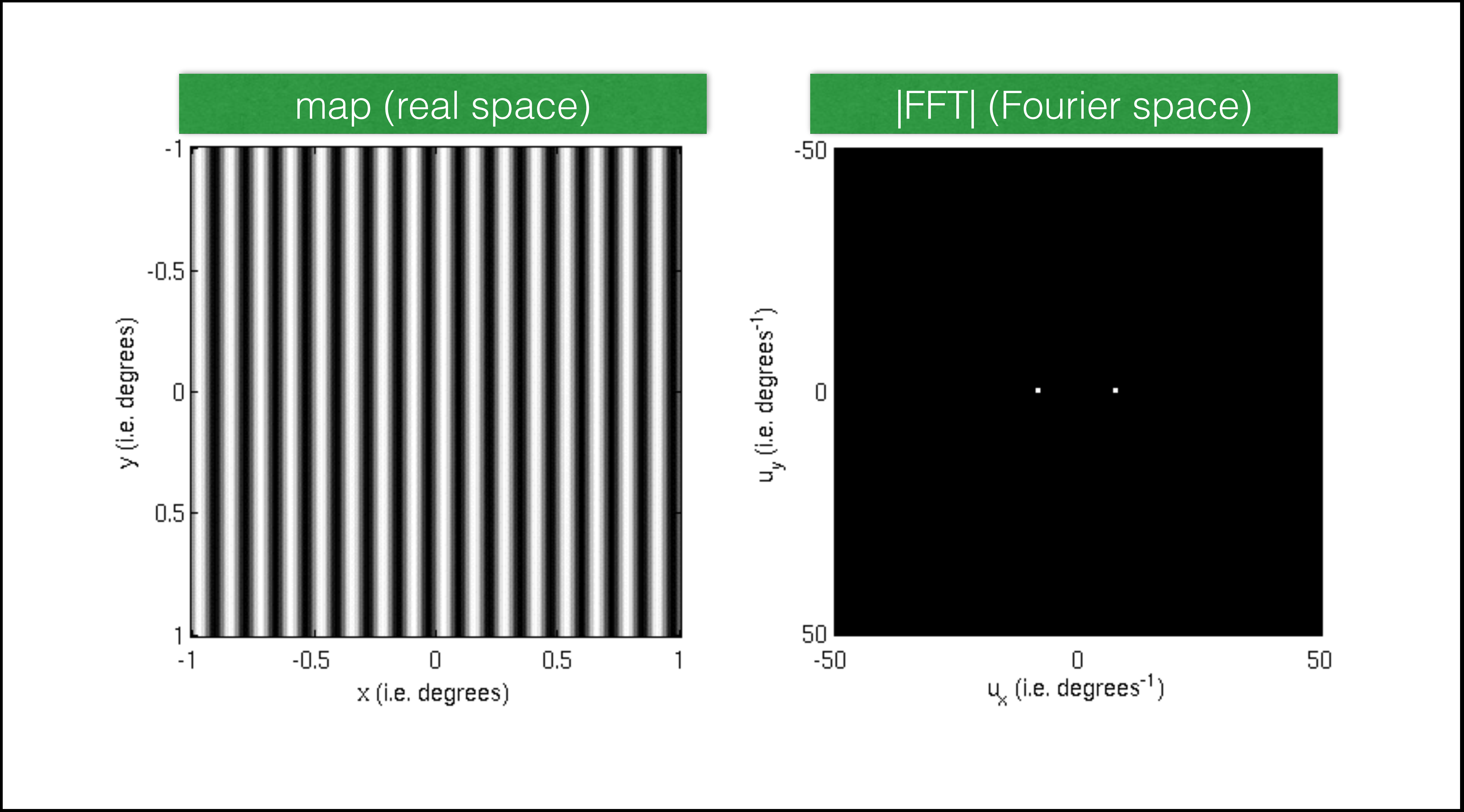
In fact, many experiments that do not do make maps of the full sky do Fourier analysis and never compute a spherical harmonic transform.

Flat sky approximation



Flat sky approximation



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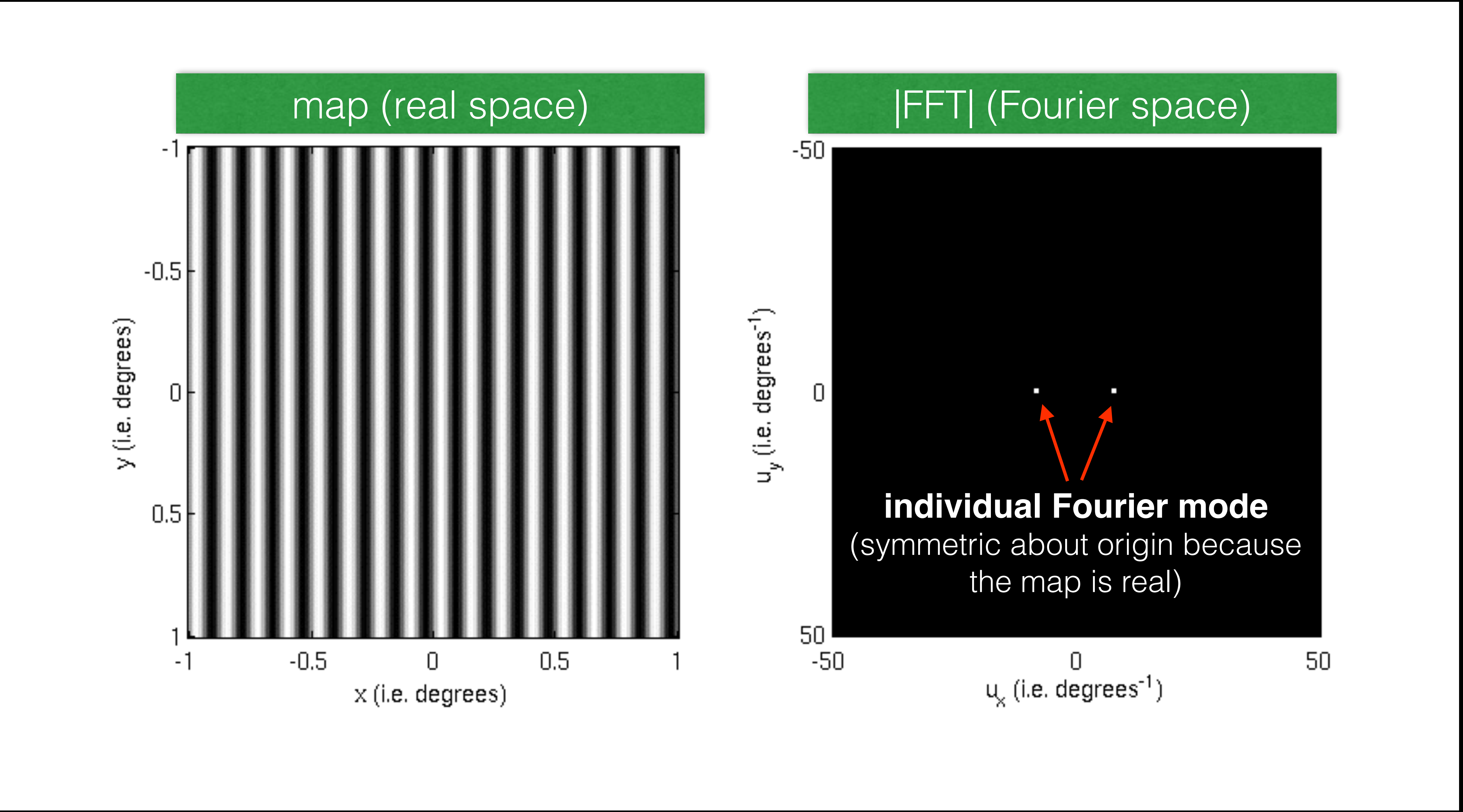
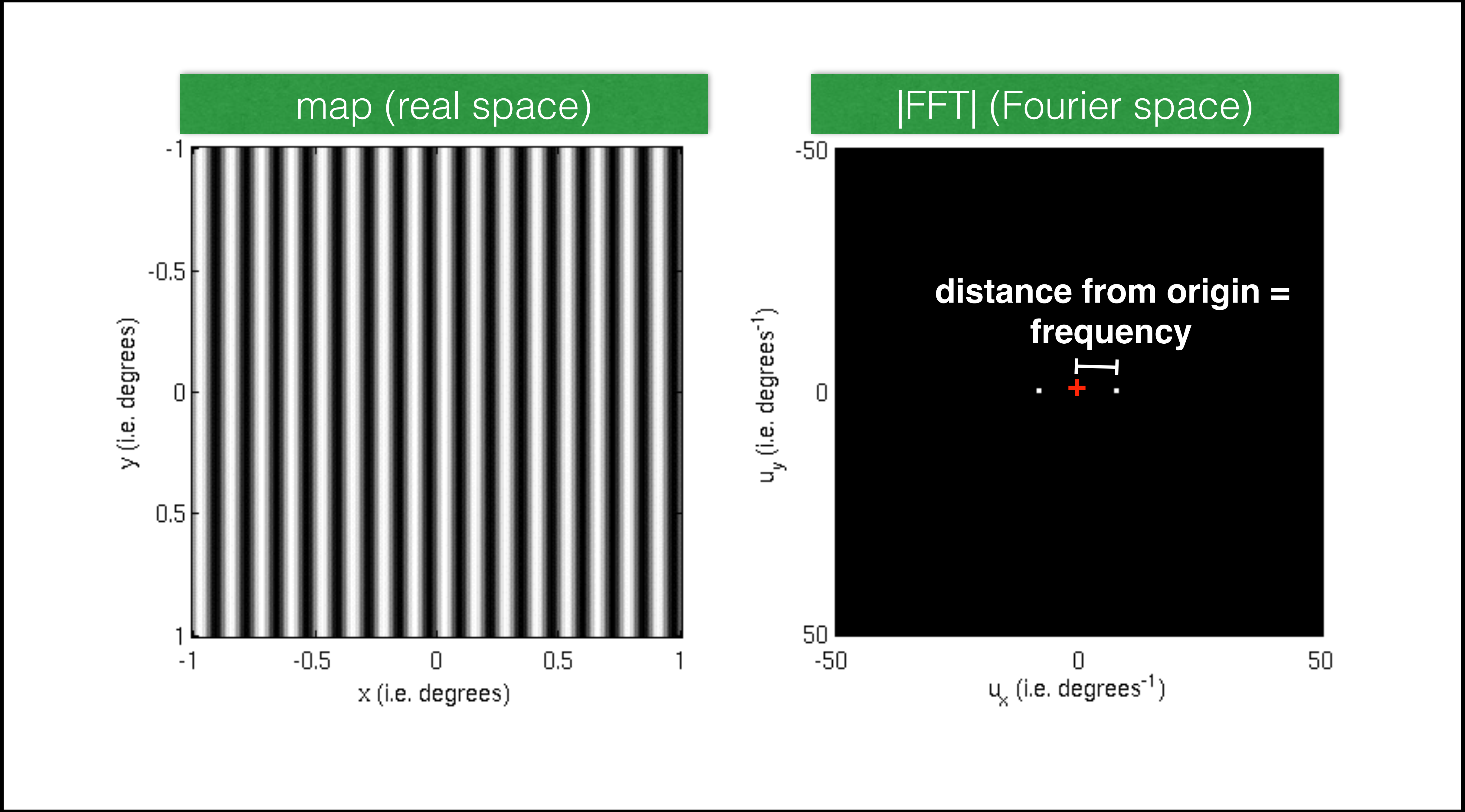
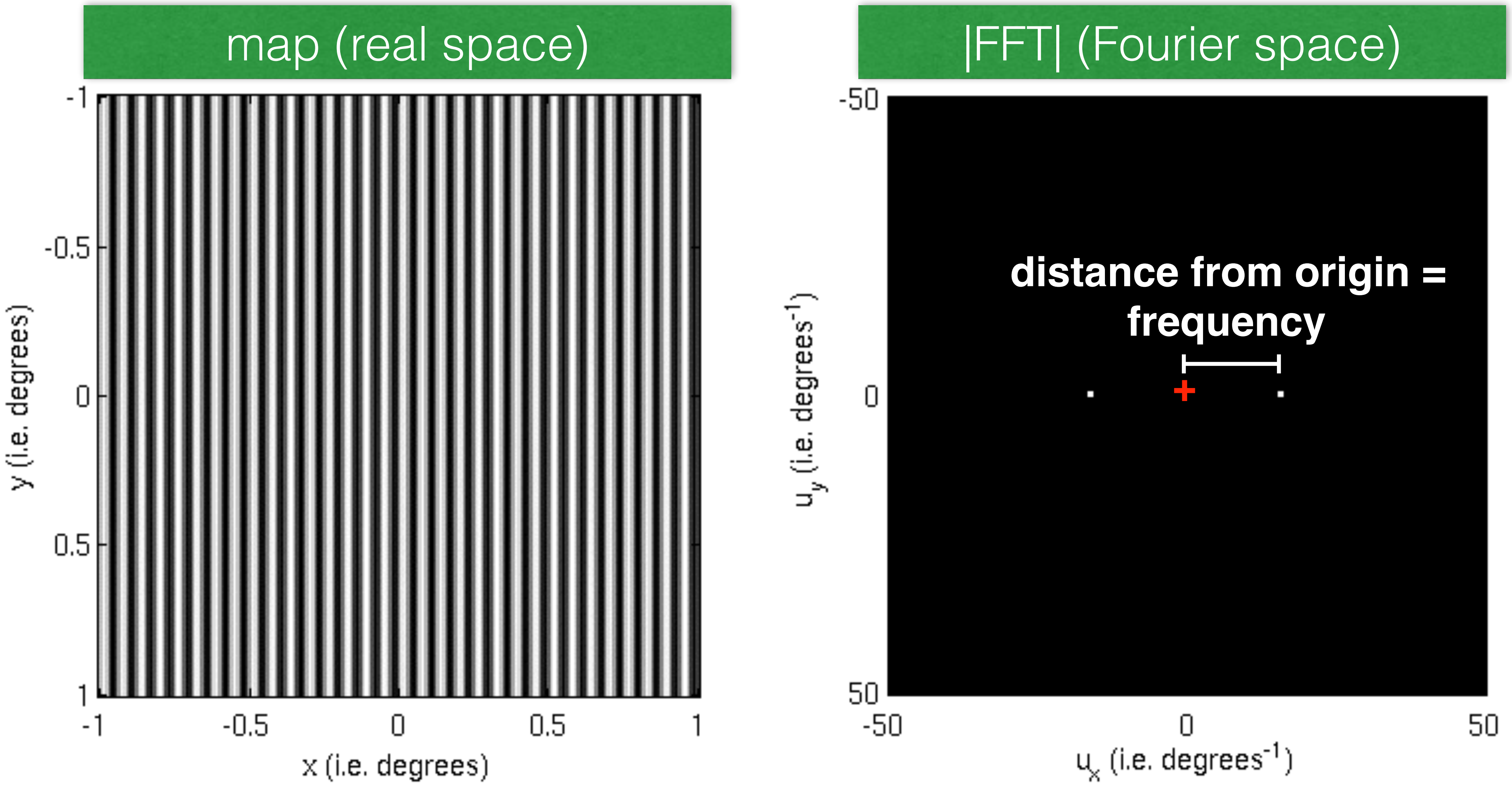


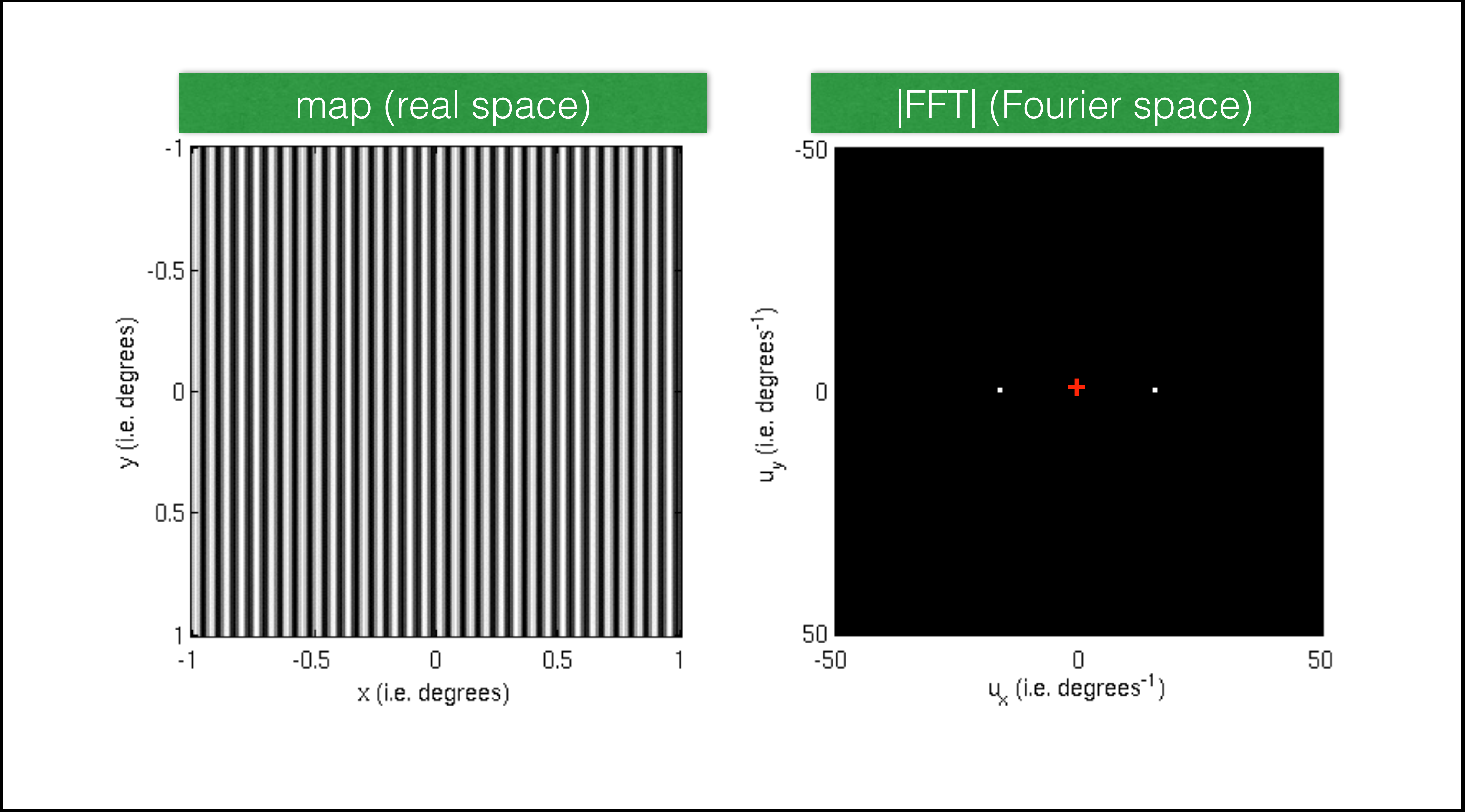
Flat sky approximation



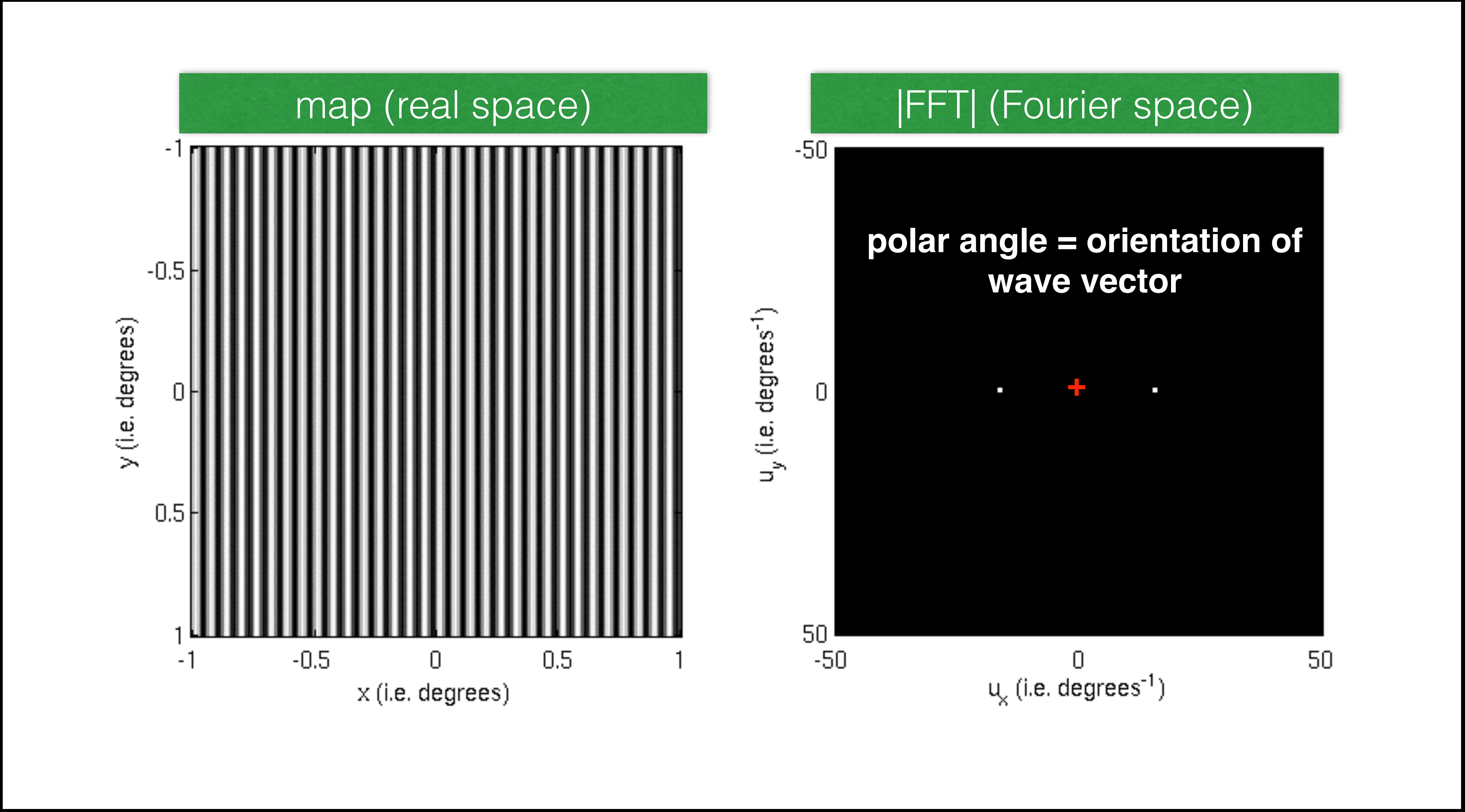
Flat sky approximation



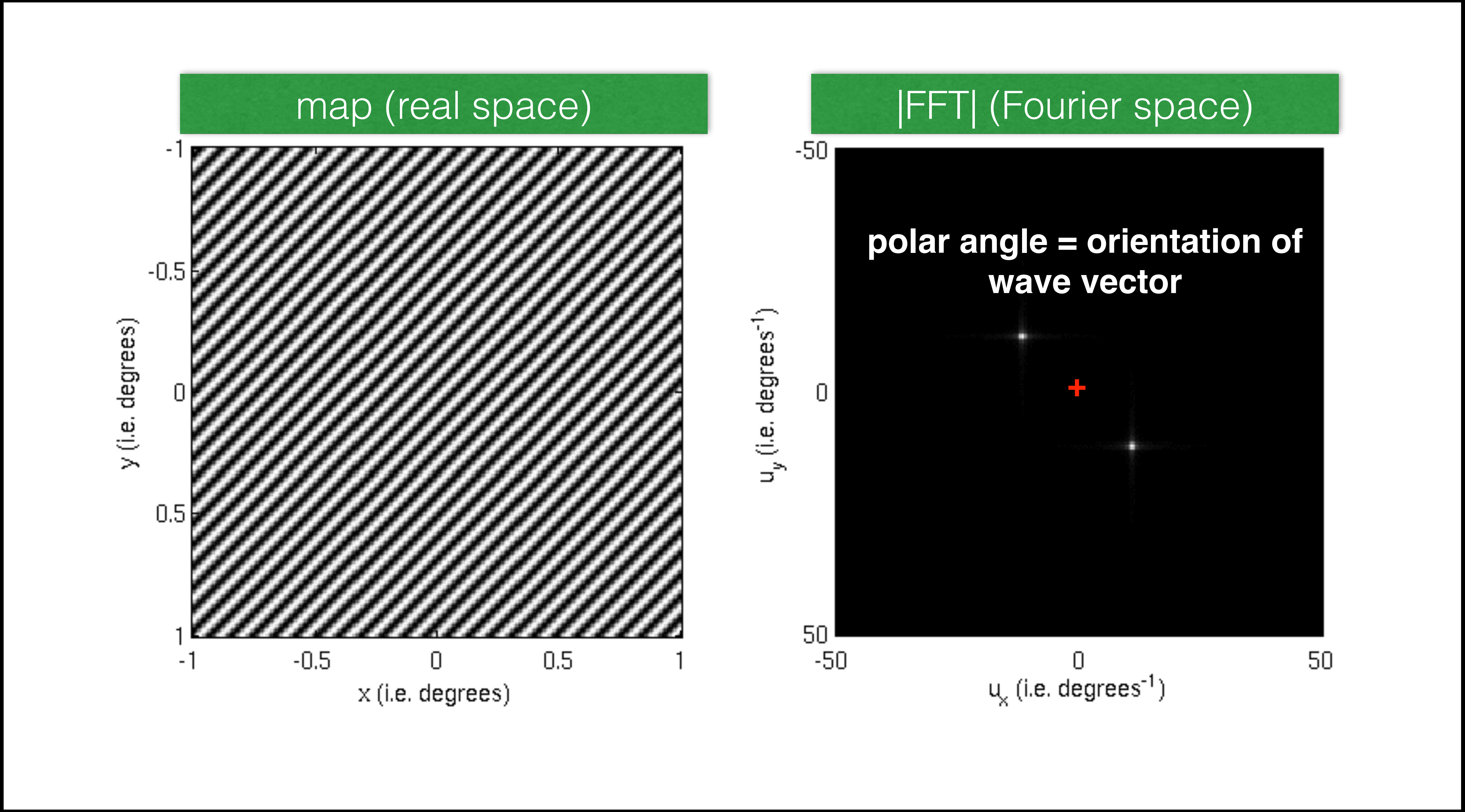
Flat sky approximation



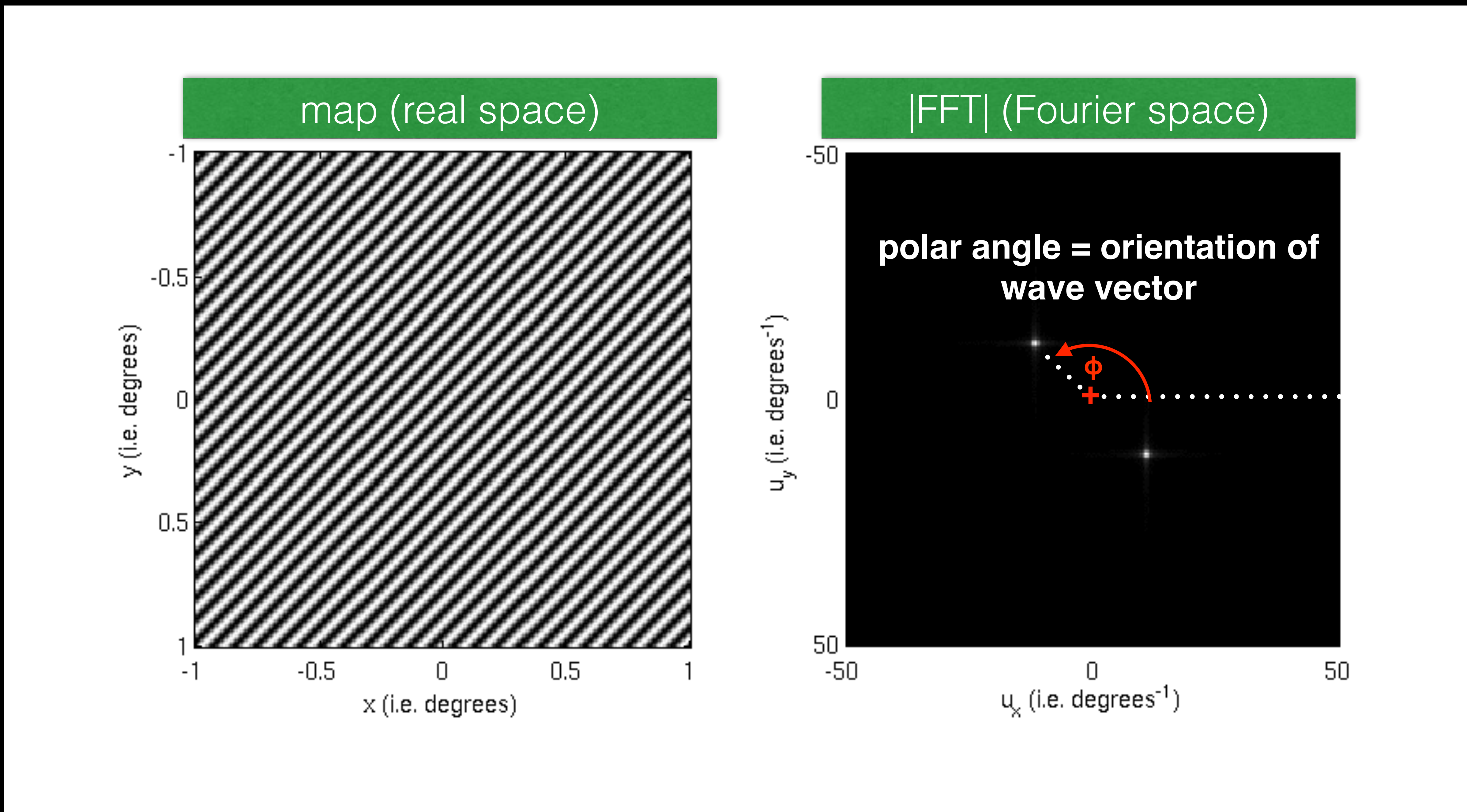
Flat sky approximation



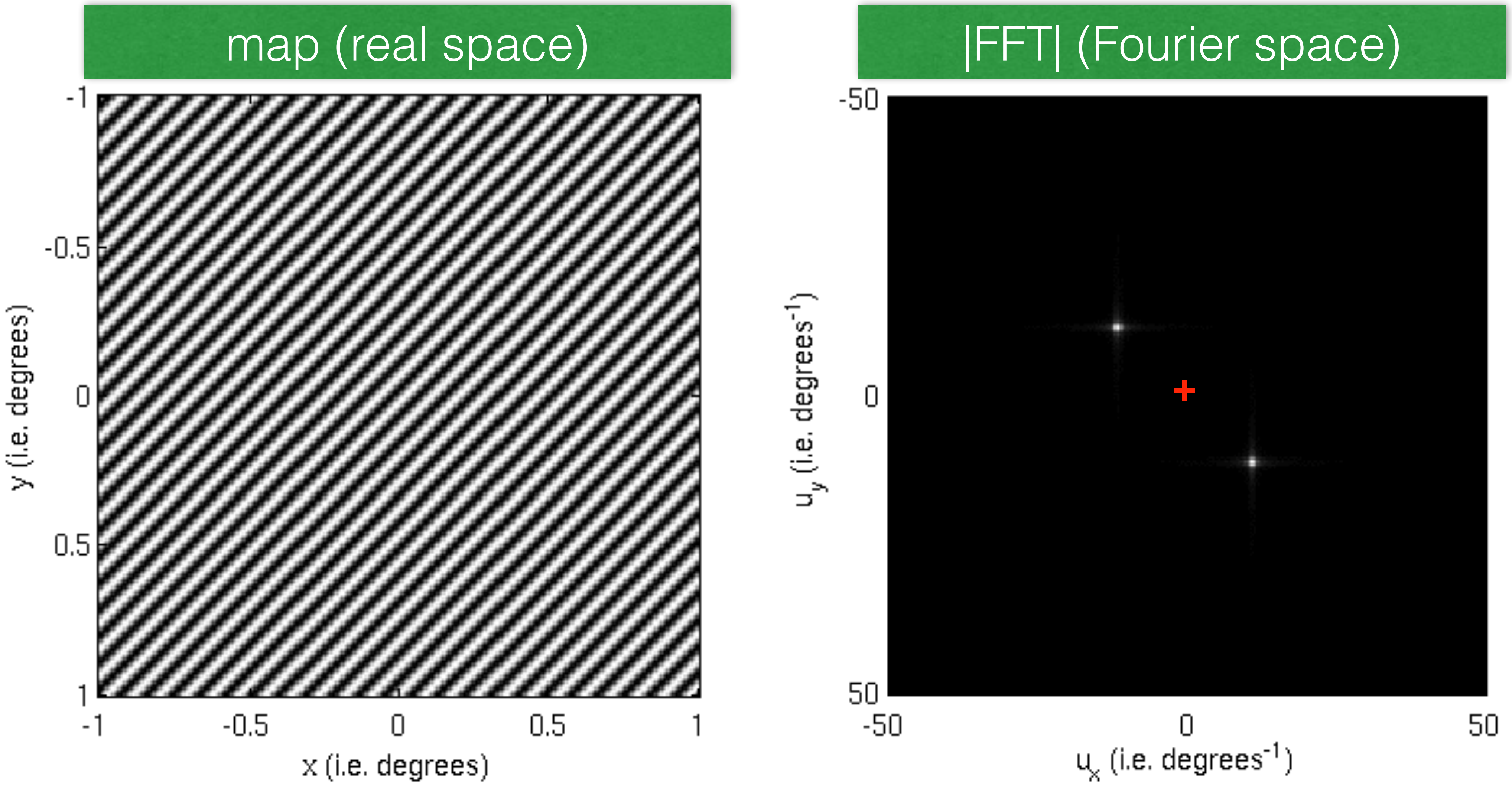
Flat sky approximation



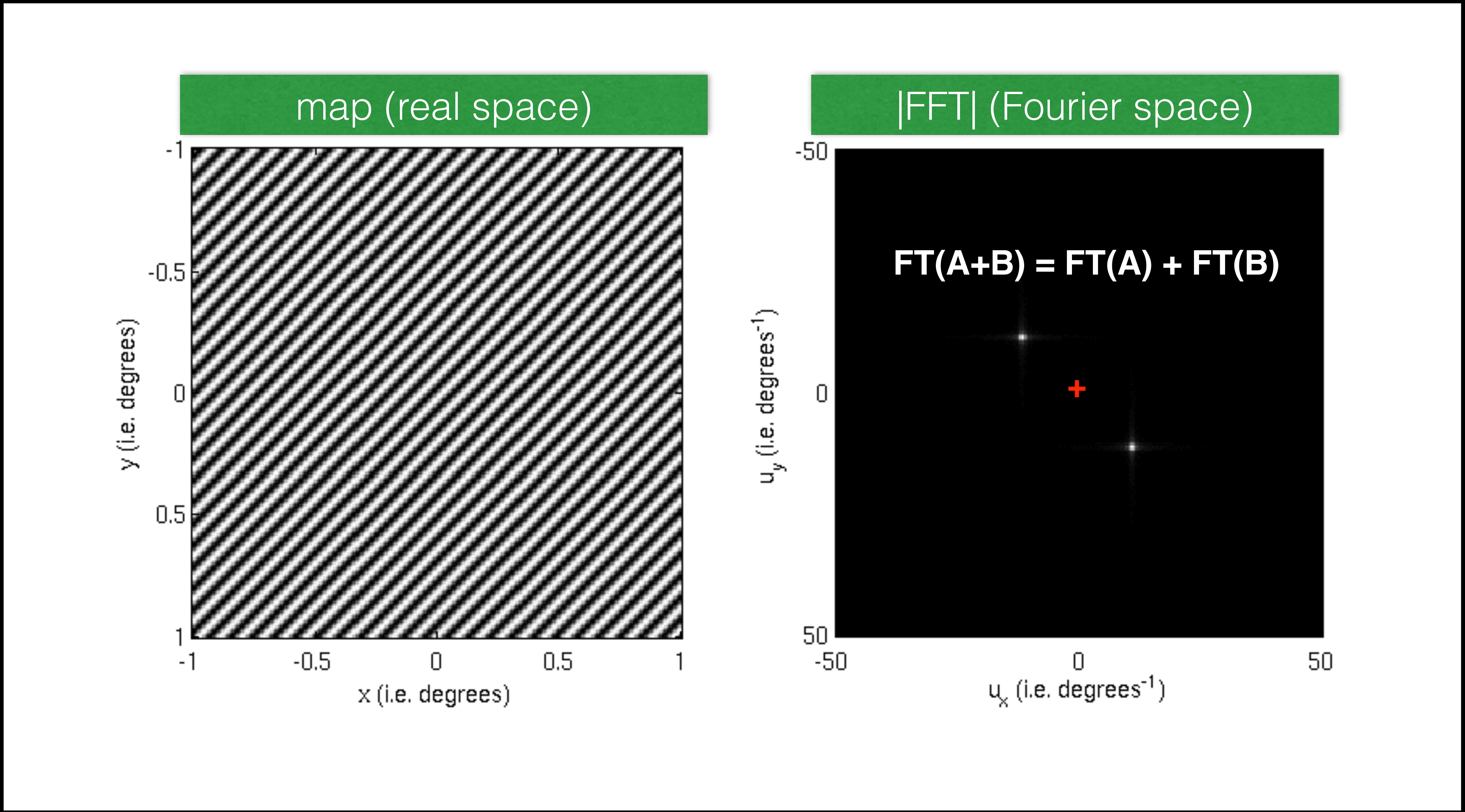
Flat sky approximation



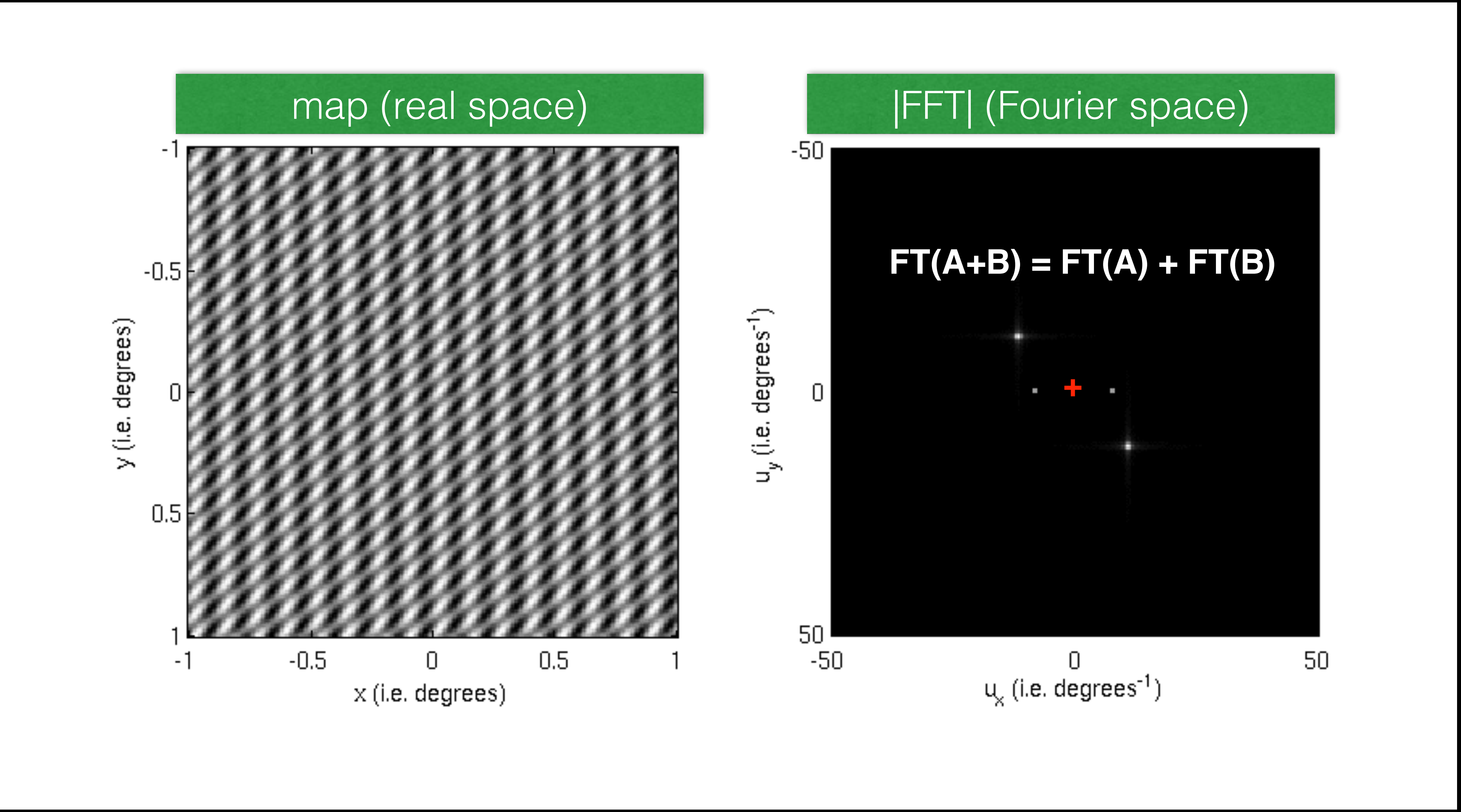
Flat sky approximation



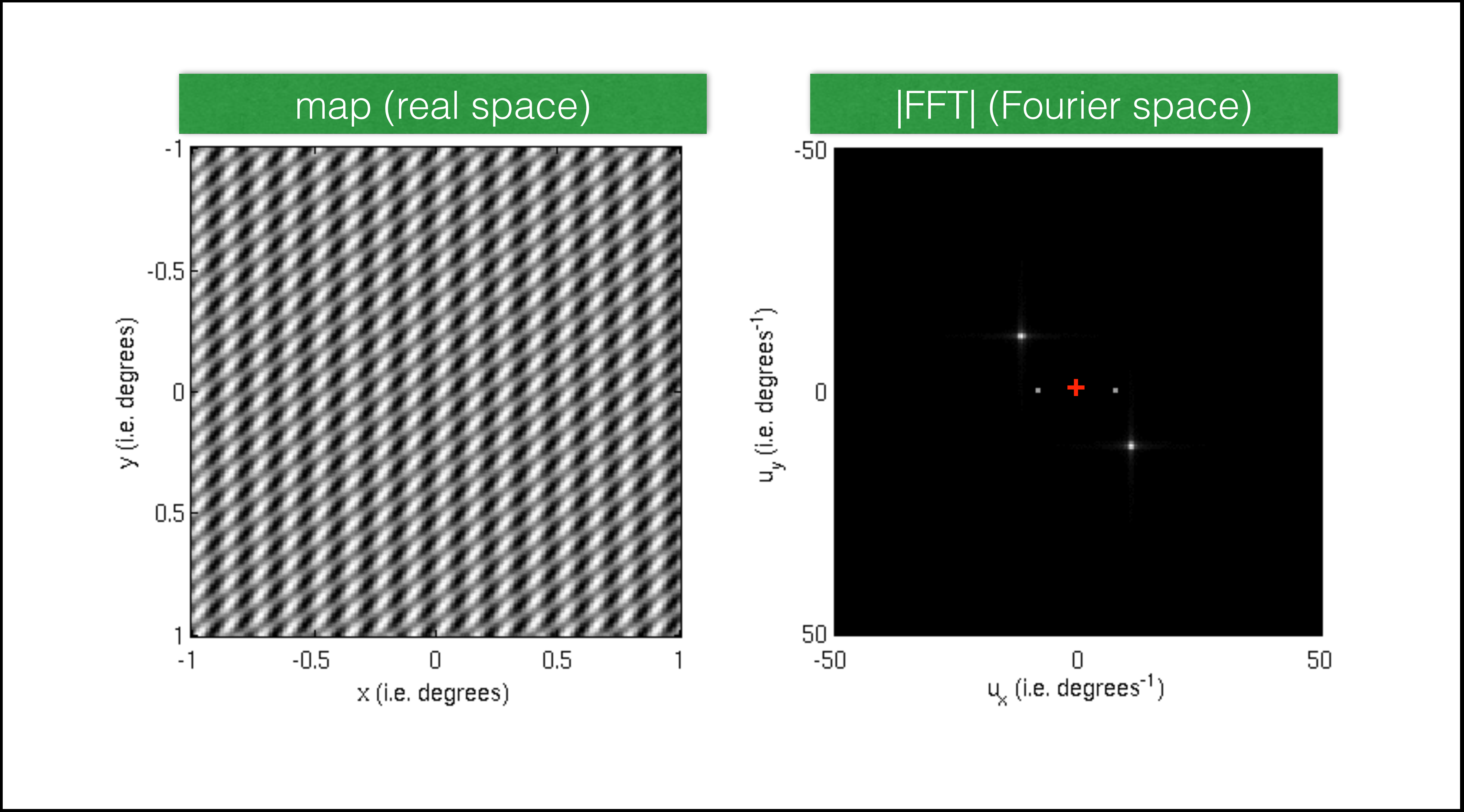
Flat sky approximation



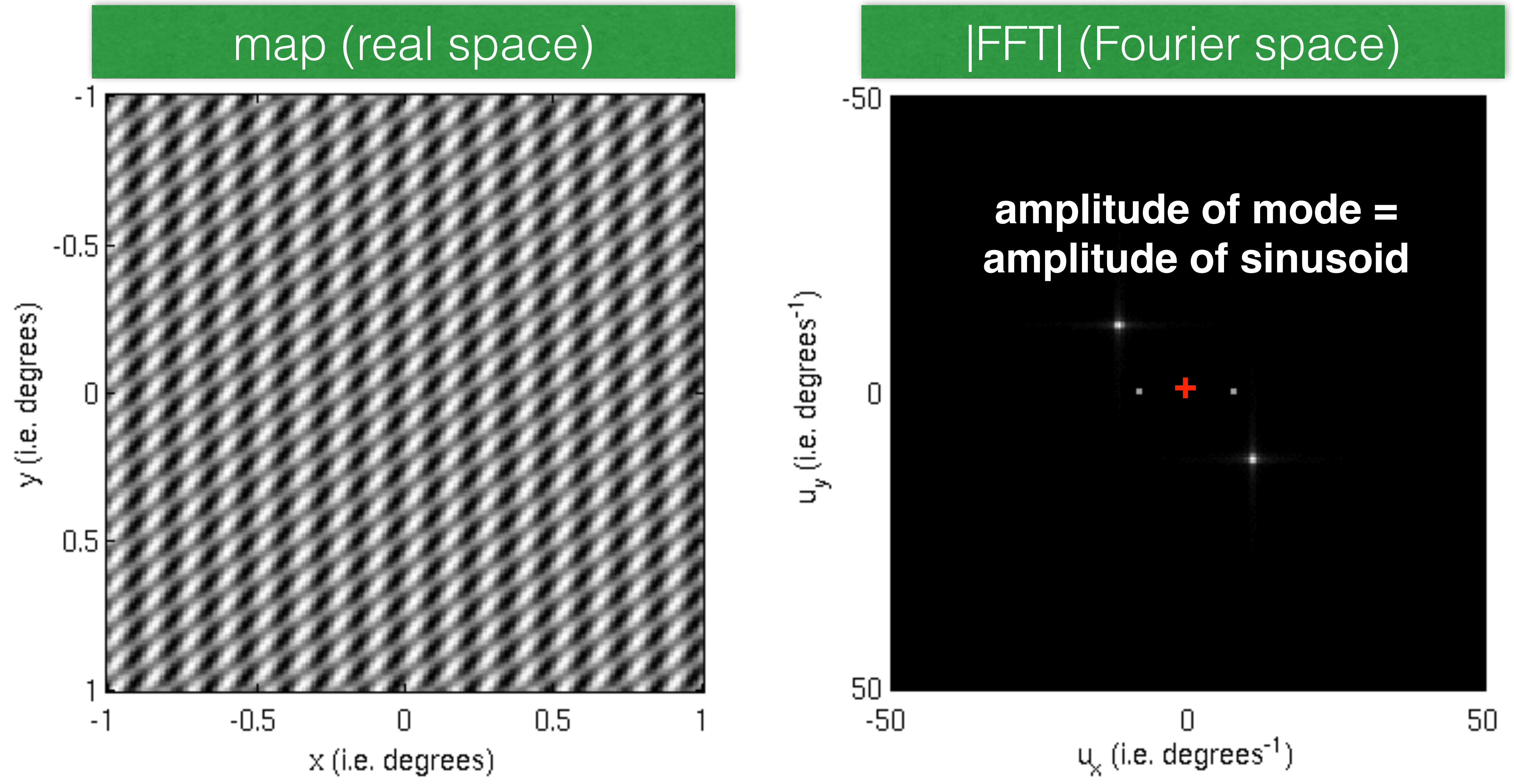
Flat sky approximation



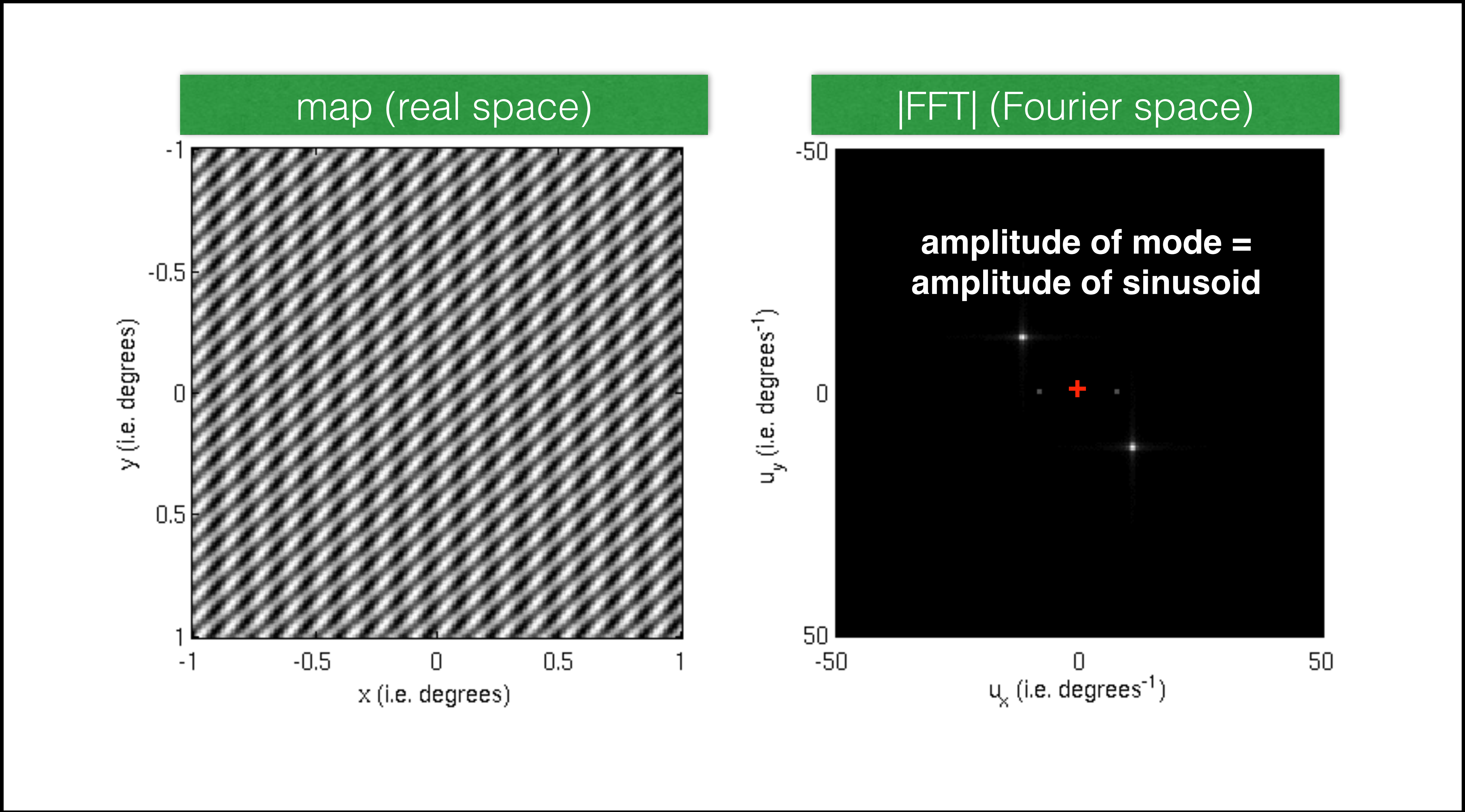
Flat sky approximation



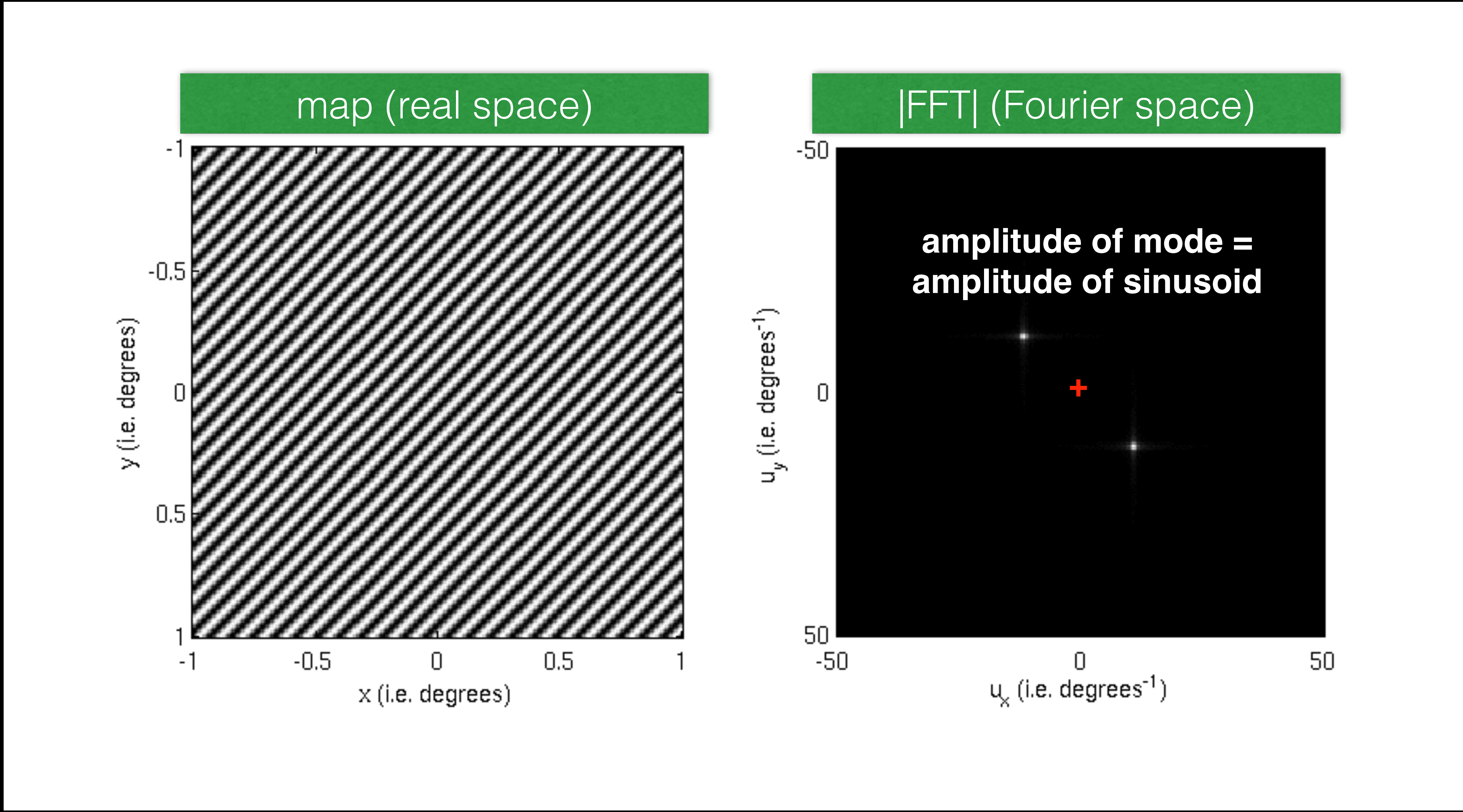
Flat sky approximation



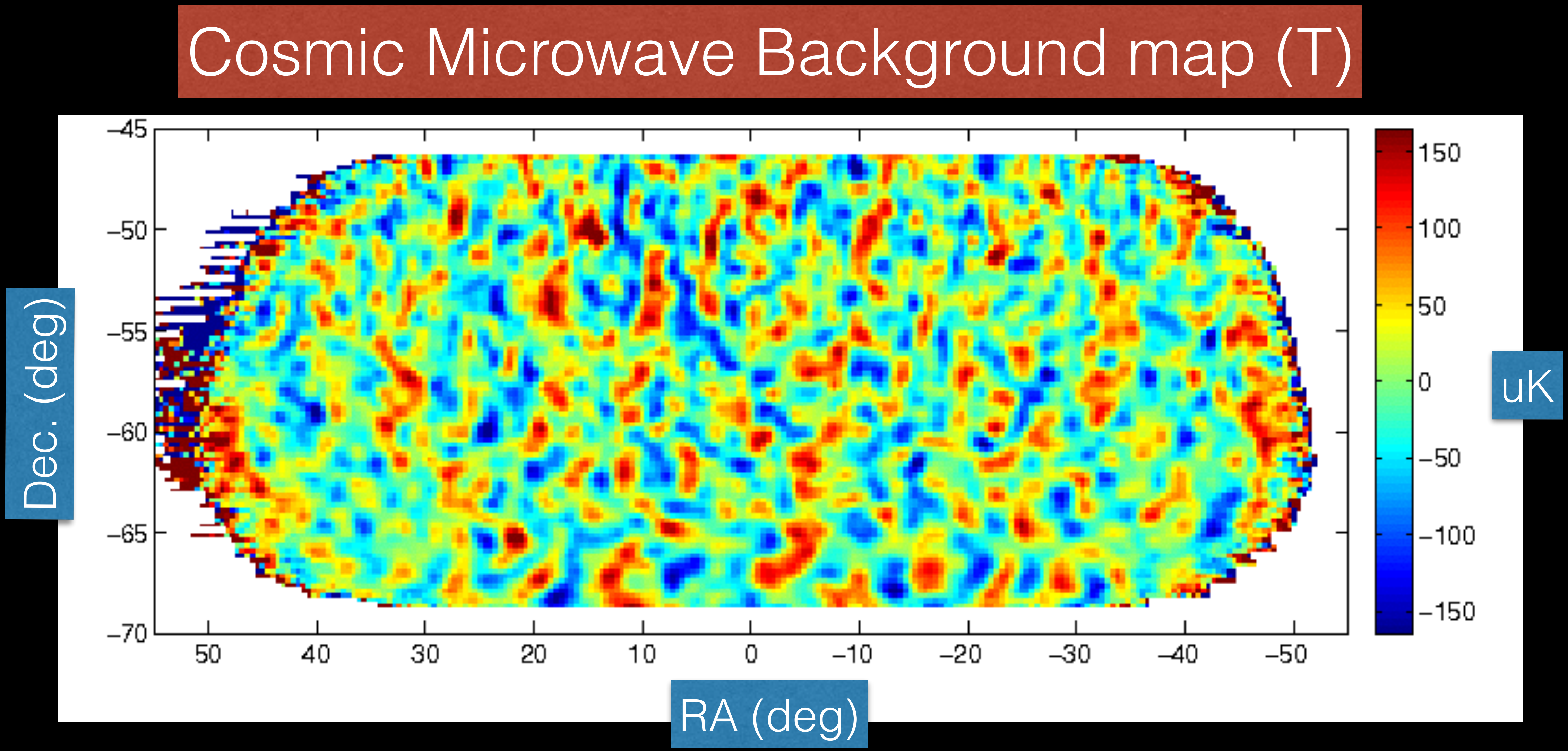
Flat sky approximation



Flat sky approximation

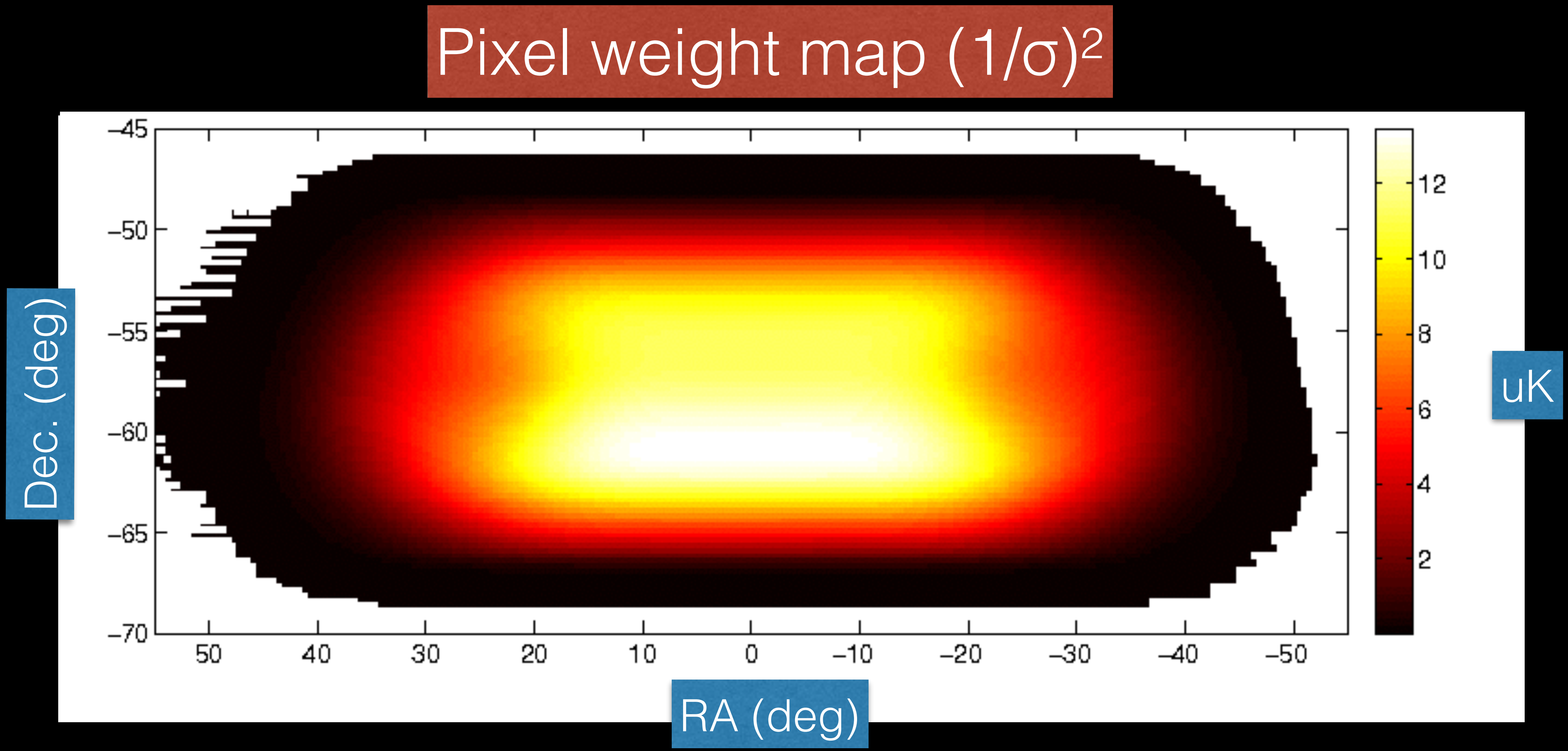


Real map



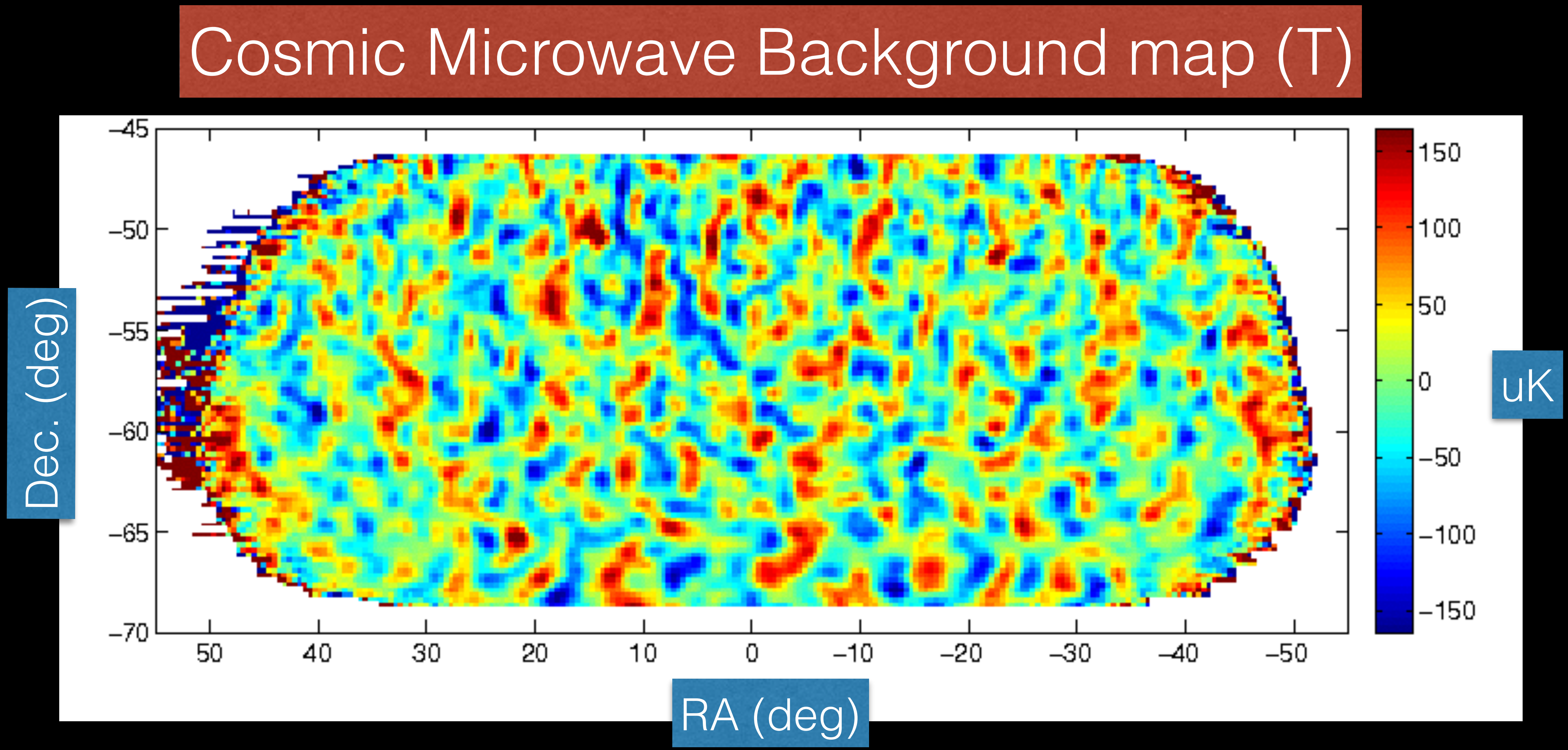
(thanks to the WMAP satellite, the CMB is often displayed with this colormap)

Real map



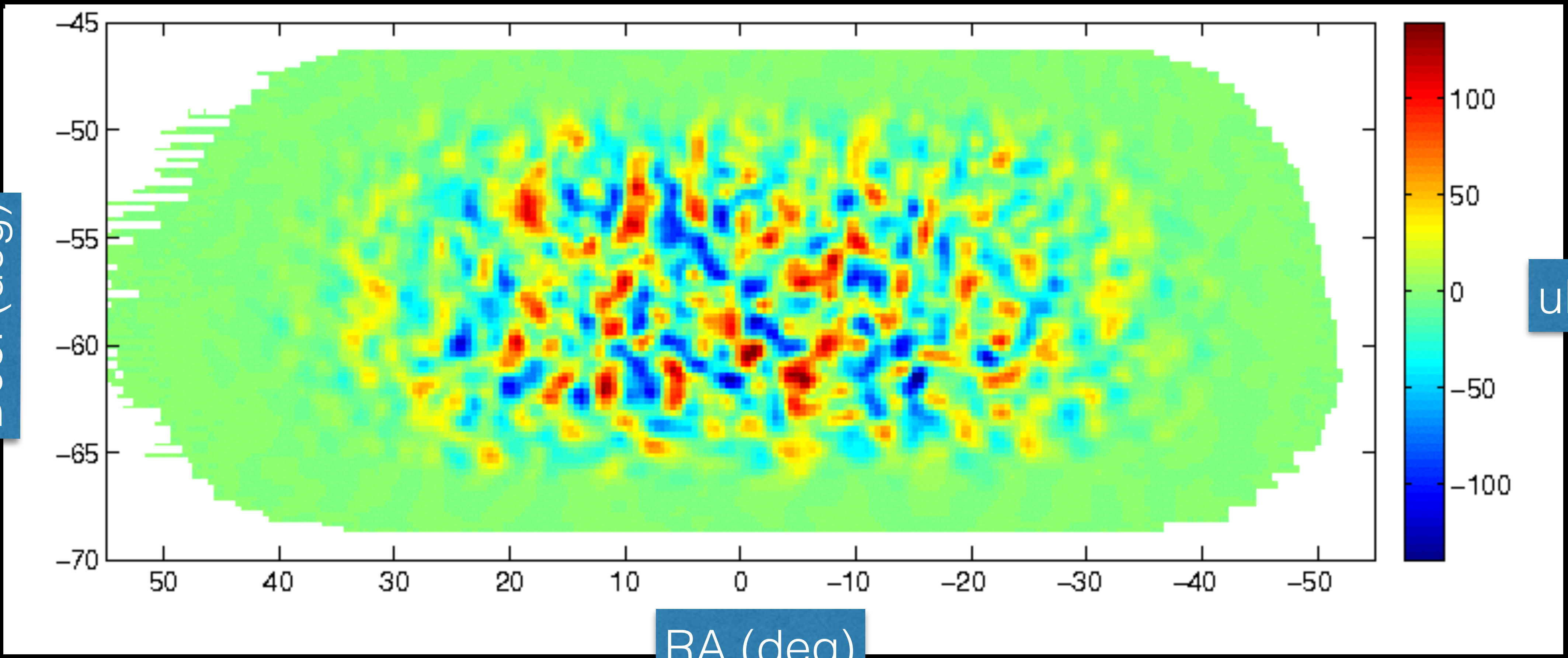
Pixel weight map $(1/\sigma)^2$
−45
−50
−55
−60
−65
−70
50
40
30
20
10
0
−10
−20
−30
−40
−50
12
10
8
6
4
2
Dec. (deg)
RA (deg)
uK

Real map


Cosmic Microwave Background map (T)
Dec. (deg)
−45
−50
−55
−60
−65
−70
50
40
30
20
10
0
−10
−20
−30
−40
−50
RA (deg)
150
100
50
0
−50
−100
−150
uK

Real map

Apodized map = map / σ^2



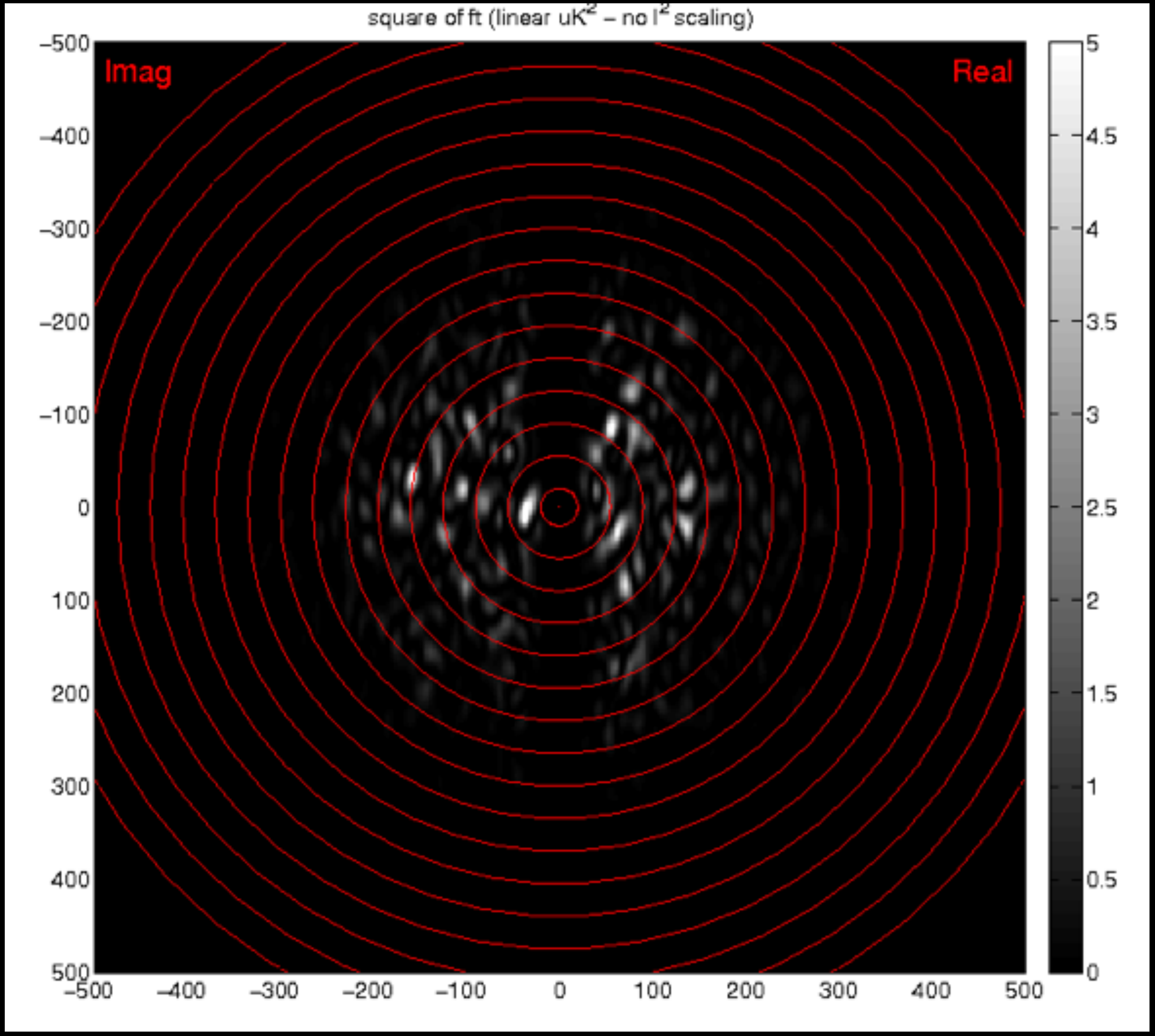
Dec. (deg)

RA (deg)

uK

Real map

|FT|^2 of zero padded, apodized map

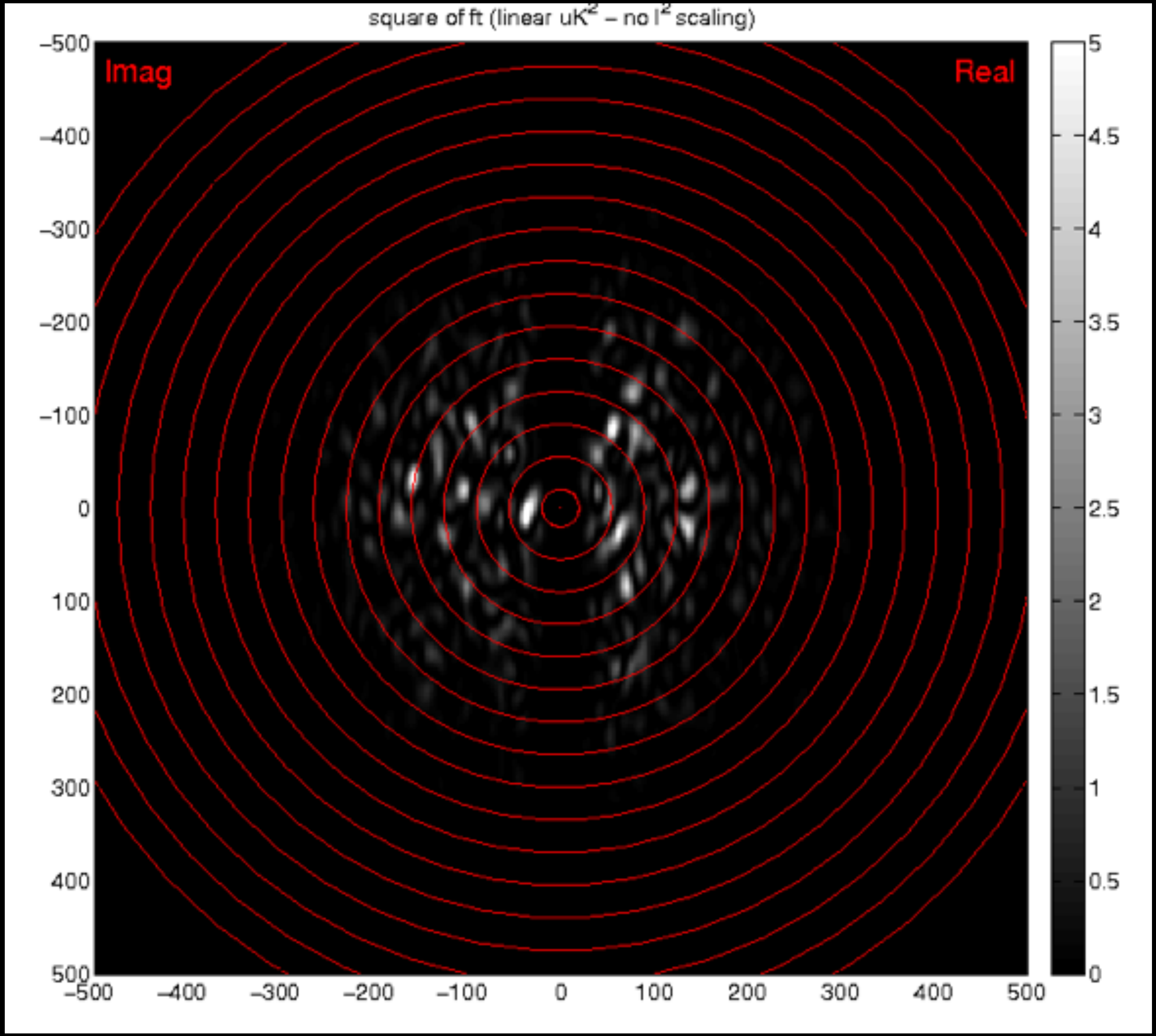


Real map

- coordinate units of map are degrees
- coordinate units of 2d Fourier plane are degrees^{-1}
- convert 2d Fourier plane coordinates to radians^{-1}
- multipole $l = 2\pi * \text{radians}^{-1}$

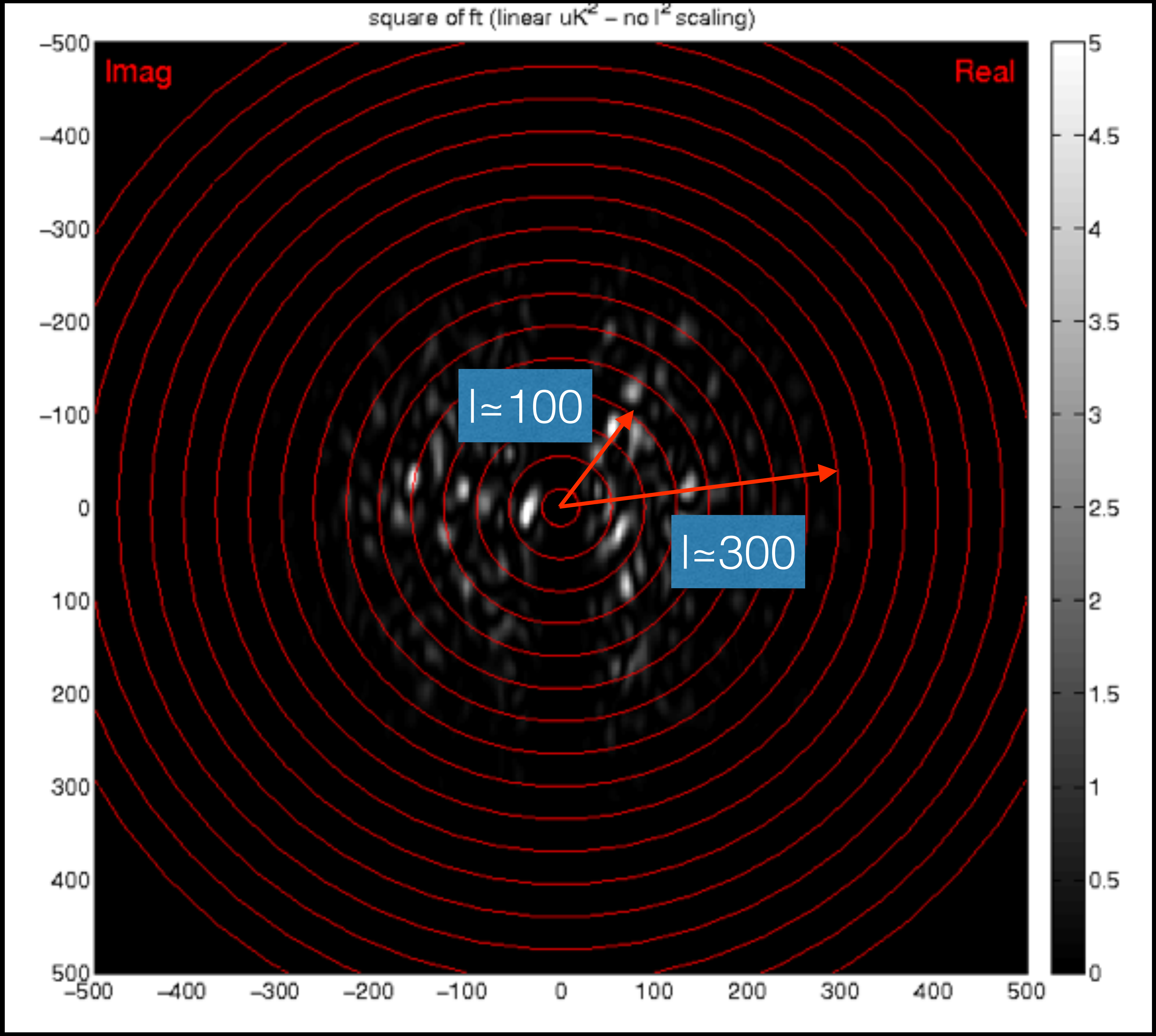
Real map

$|FT|^2$ of zero padded, apodized map



Real map

|FT|^2 of zero padded, apodized map

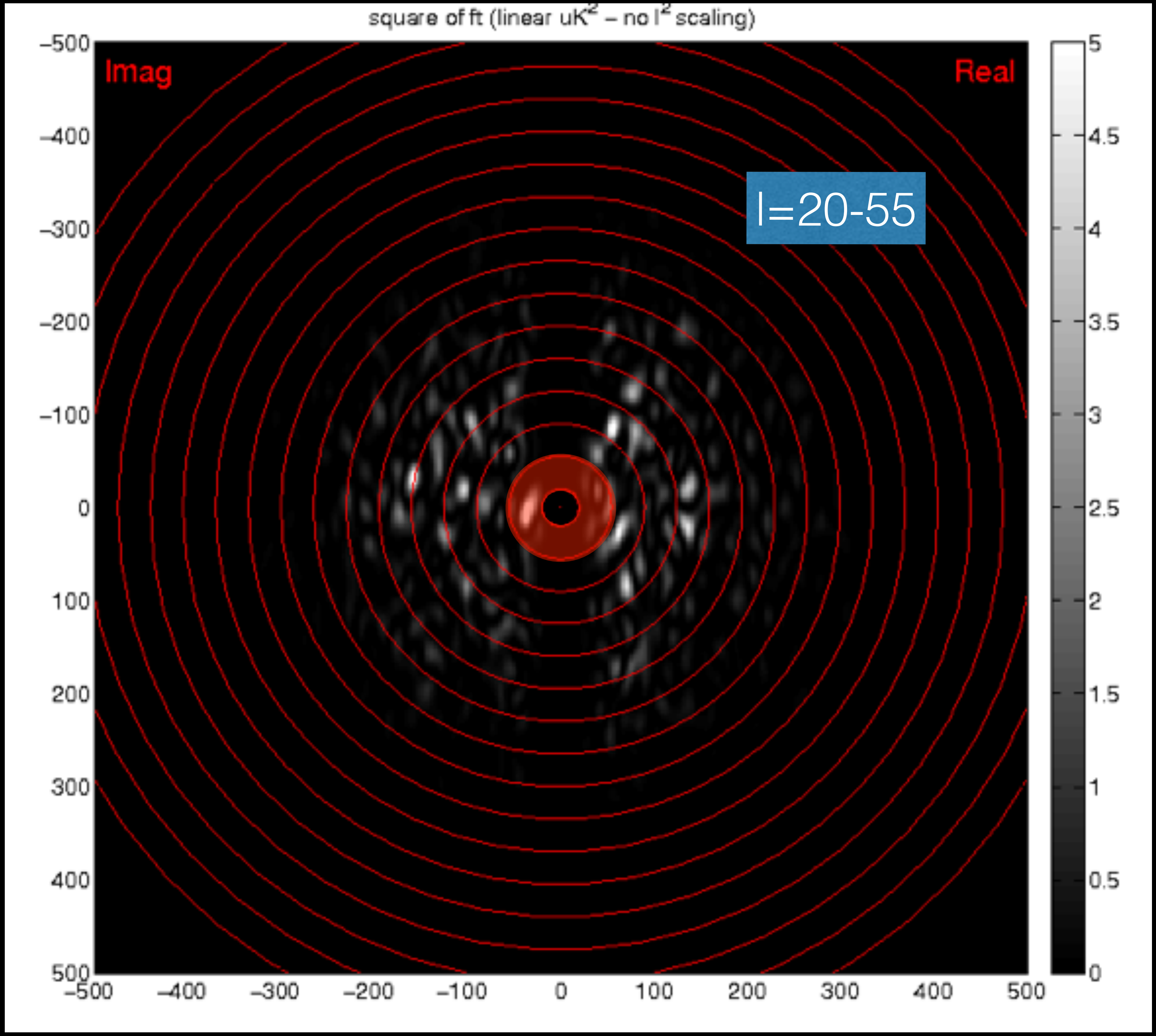


Real map

Average the signal in annular bins to make "bandpowers"

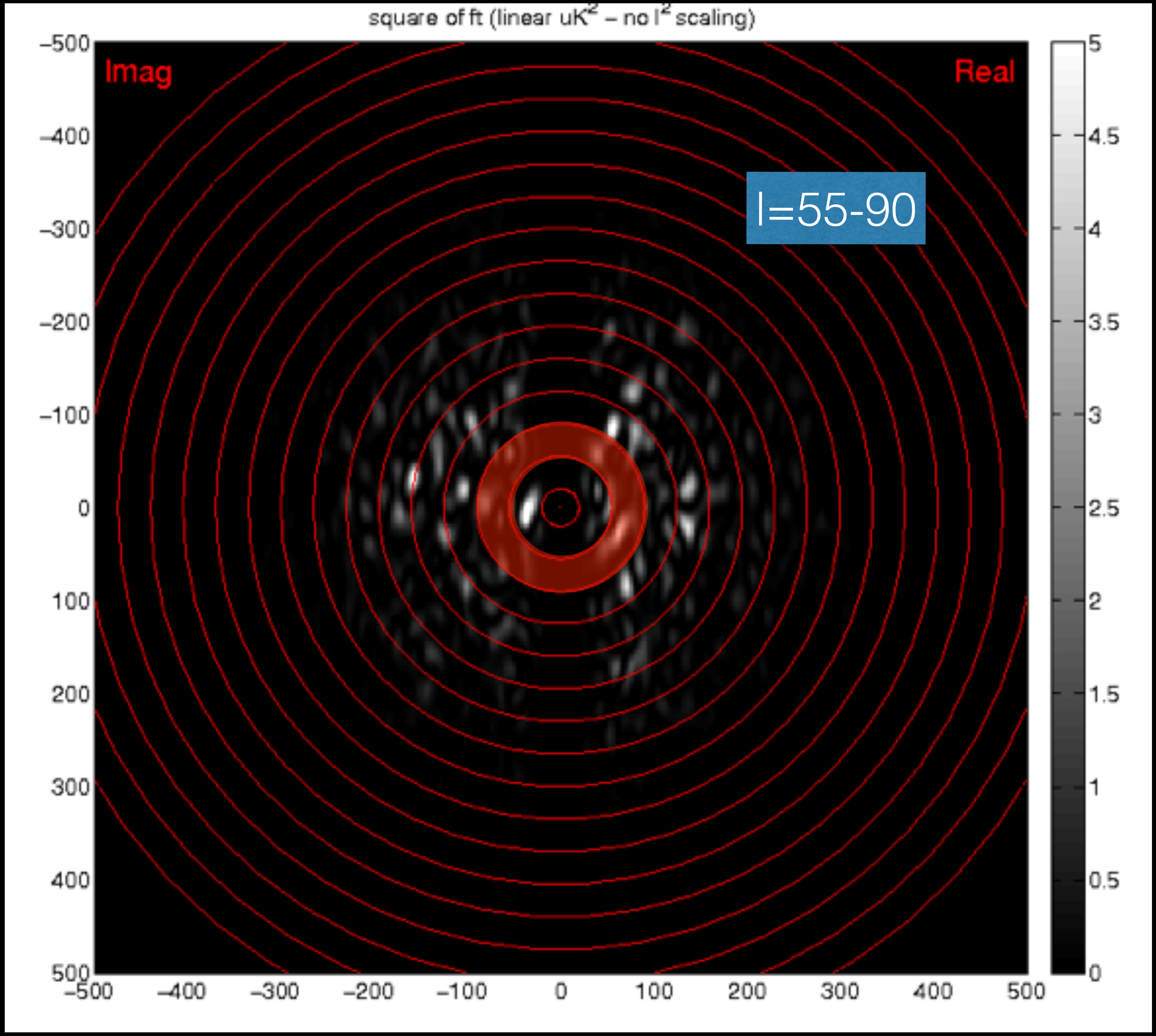
Real map

|FT|^2 of zero padded, apodized map



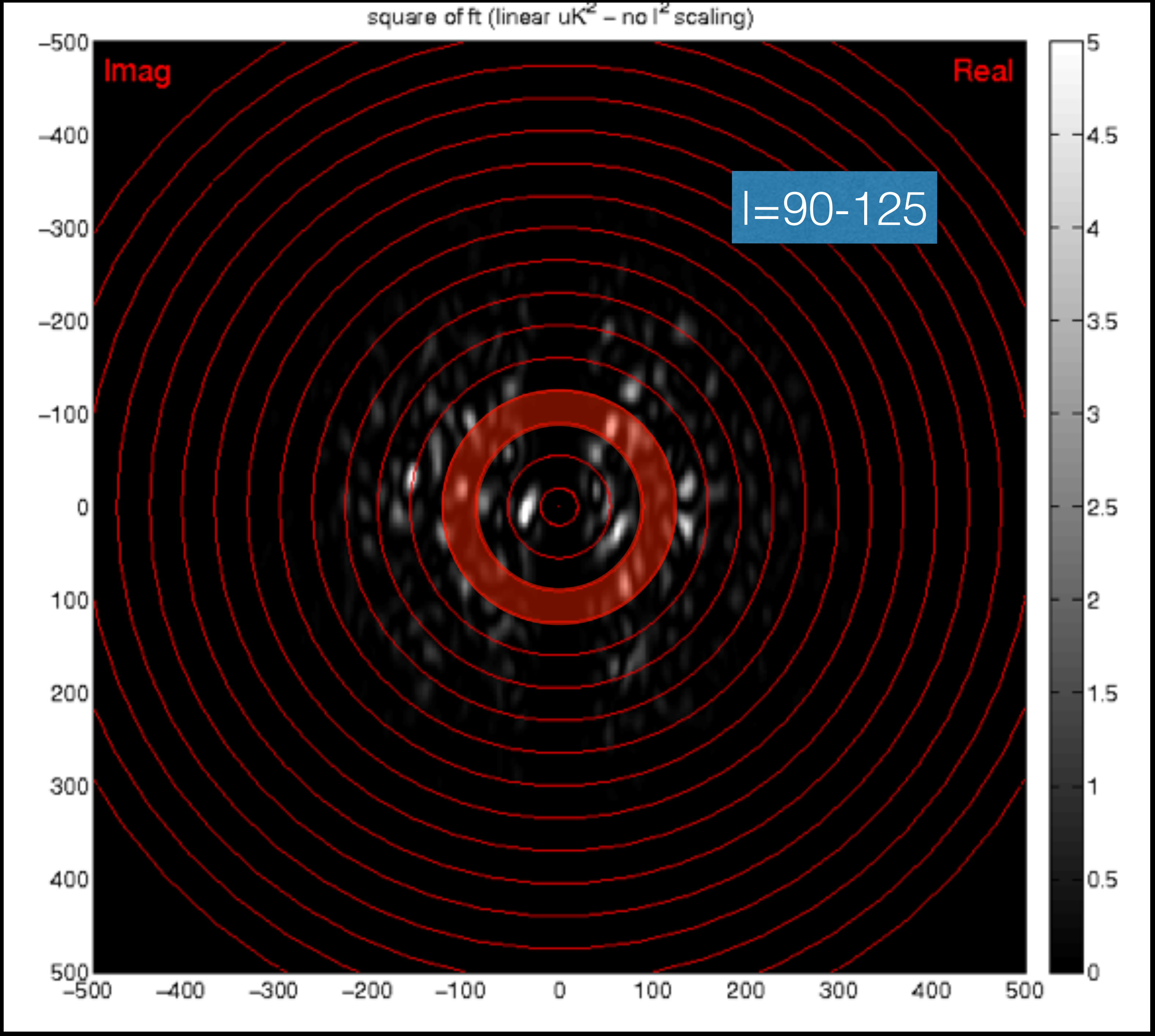
Real map

|FT|^2 of zero padded, apodized map



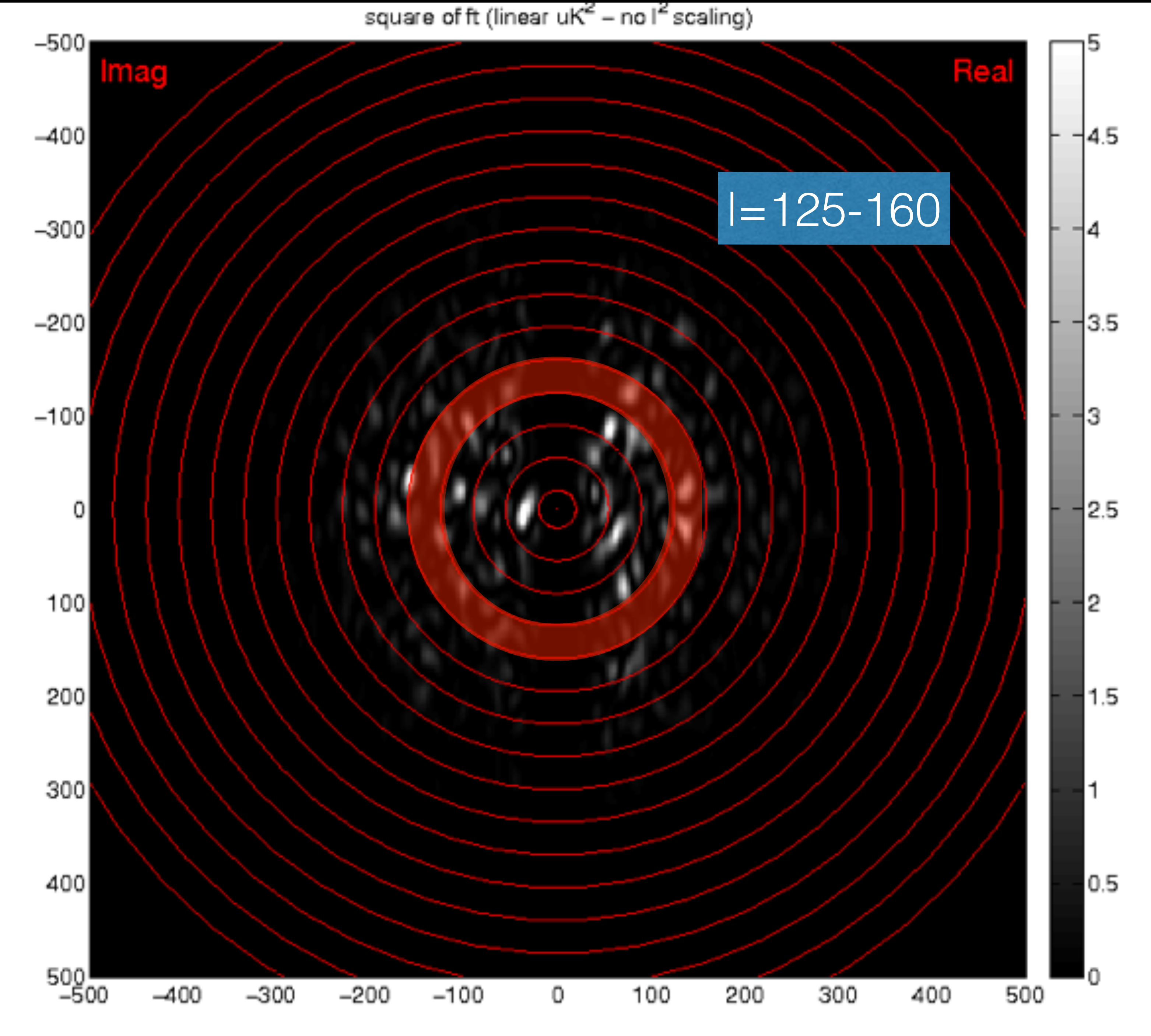
Real map

|FT|^2 of zero padded, apodized map



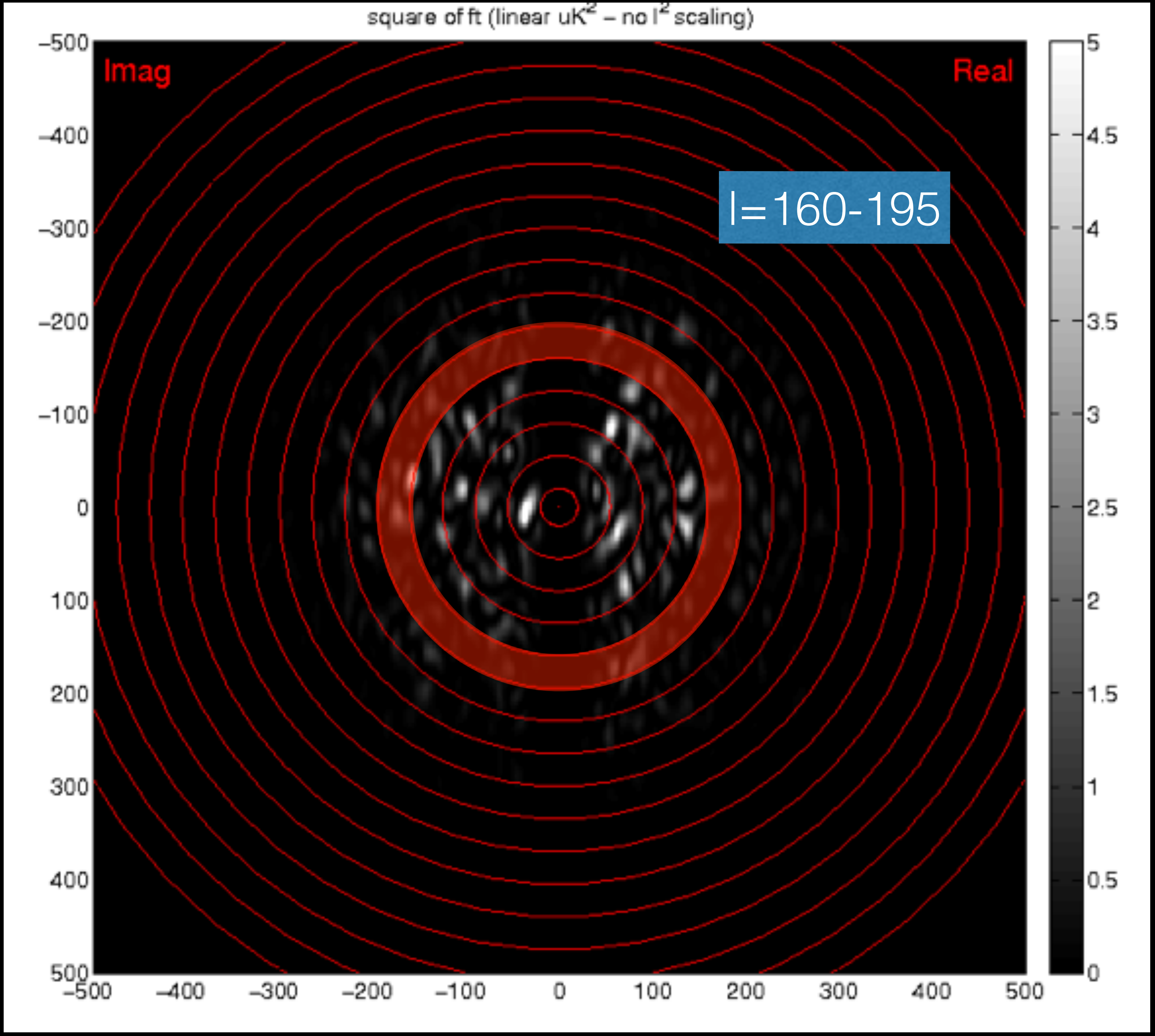
Real map

|FT|^2 of zero padded, apodized map



Real map

|FT|^2 of zero padded, apodized map



This gets us a power spectrum — just data points without error bars.

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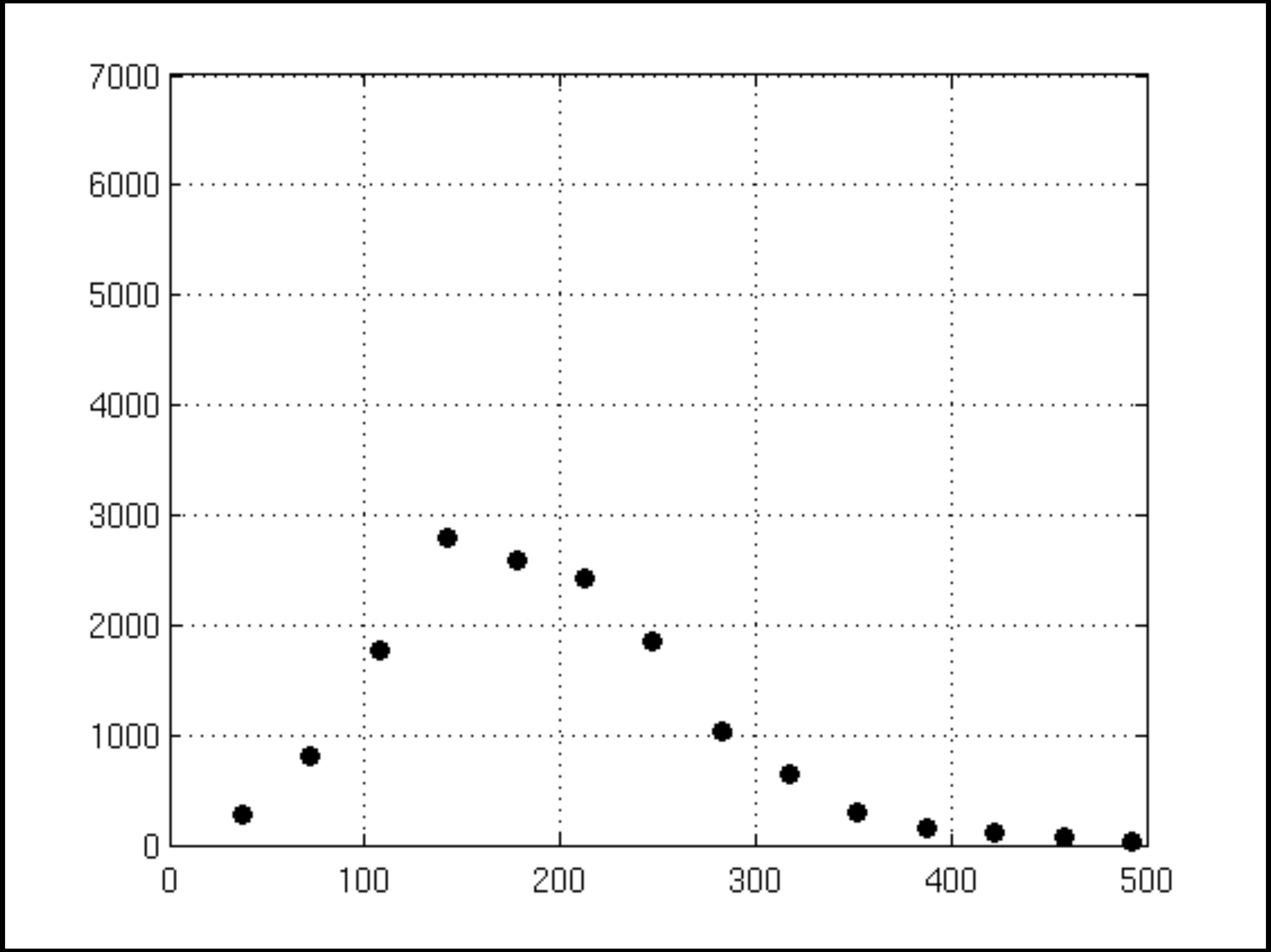


average in annulus x l(l+1)/2π

multipole l

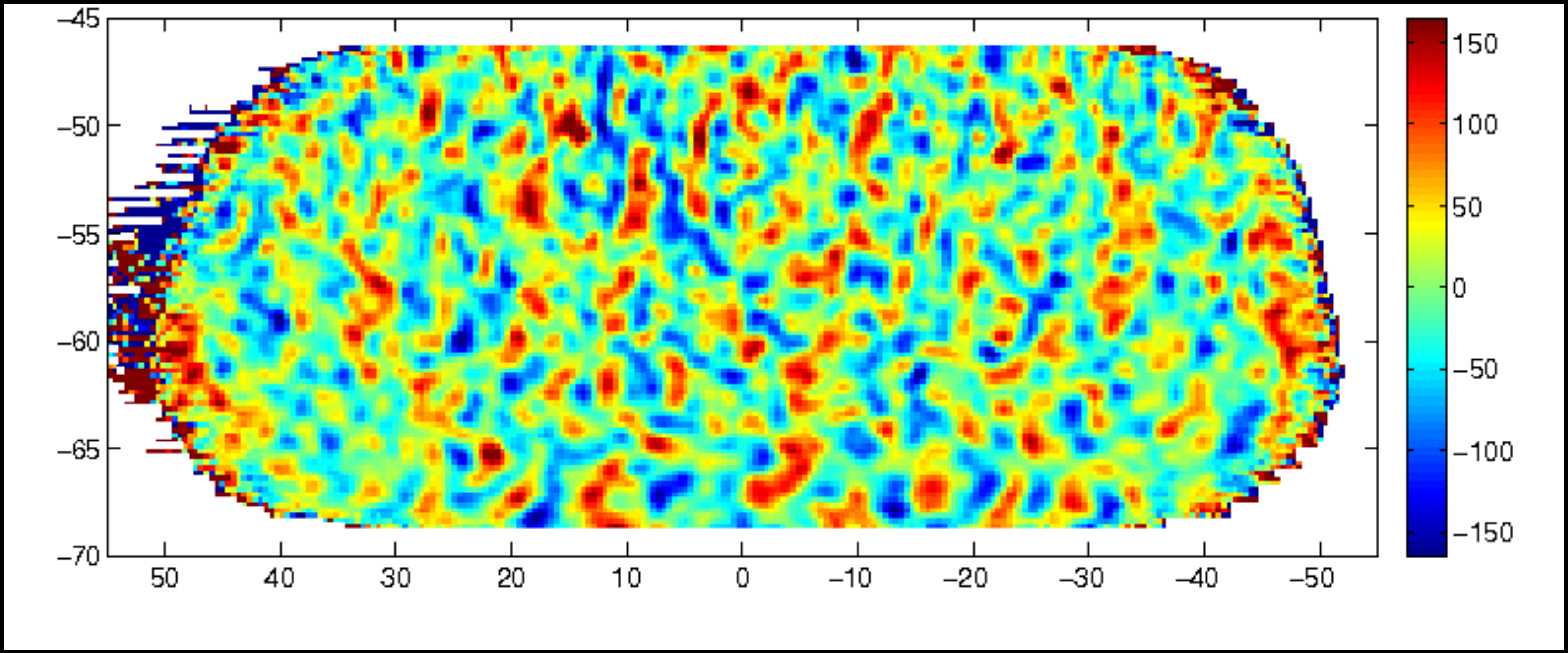
Now we need to assign error bars.

Monte Carlo analysis

- One simple way to estimate noise is to make a map from one half of the data set, make a map from the second half, and difference them. Signal goes away but resulting map has same noise properties as the real map.

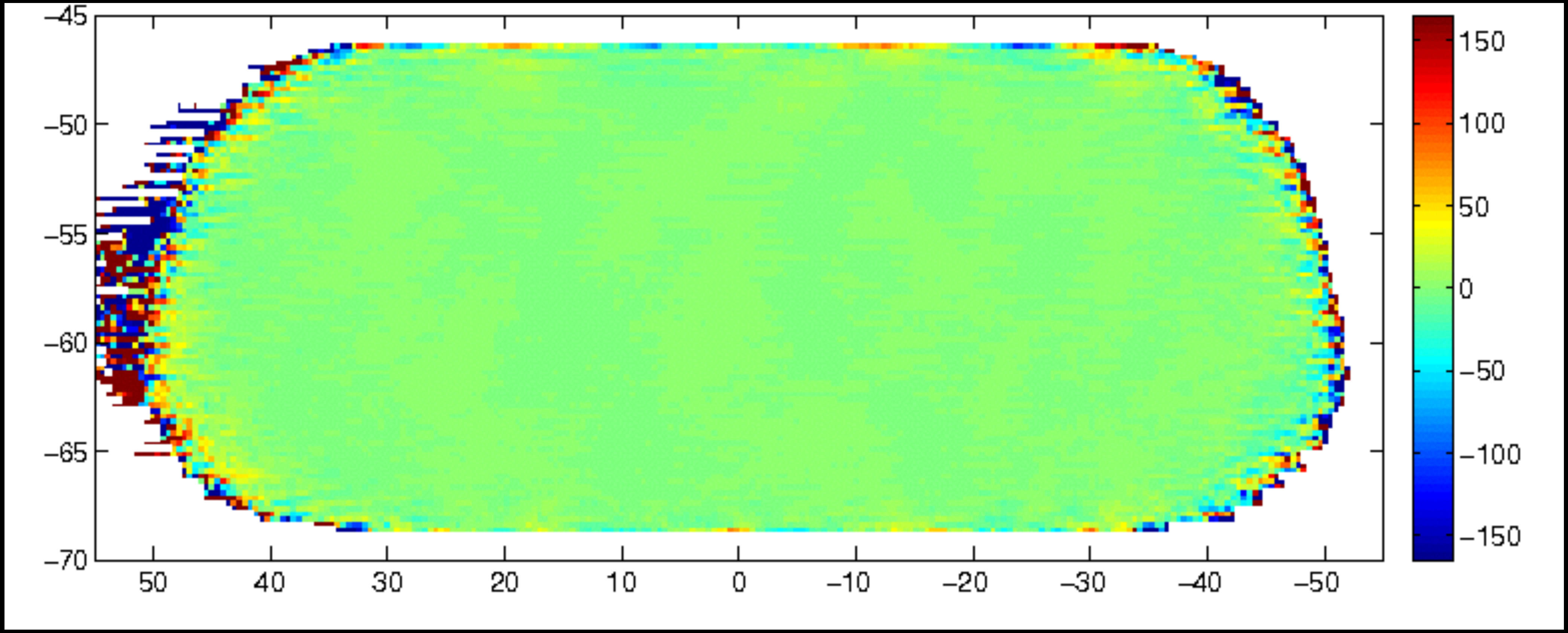
Monte Carlo analysis

Real map

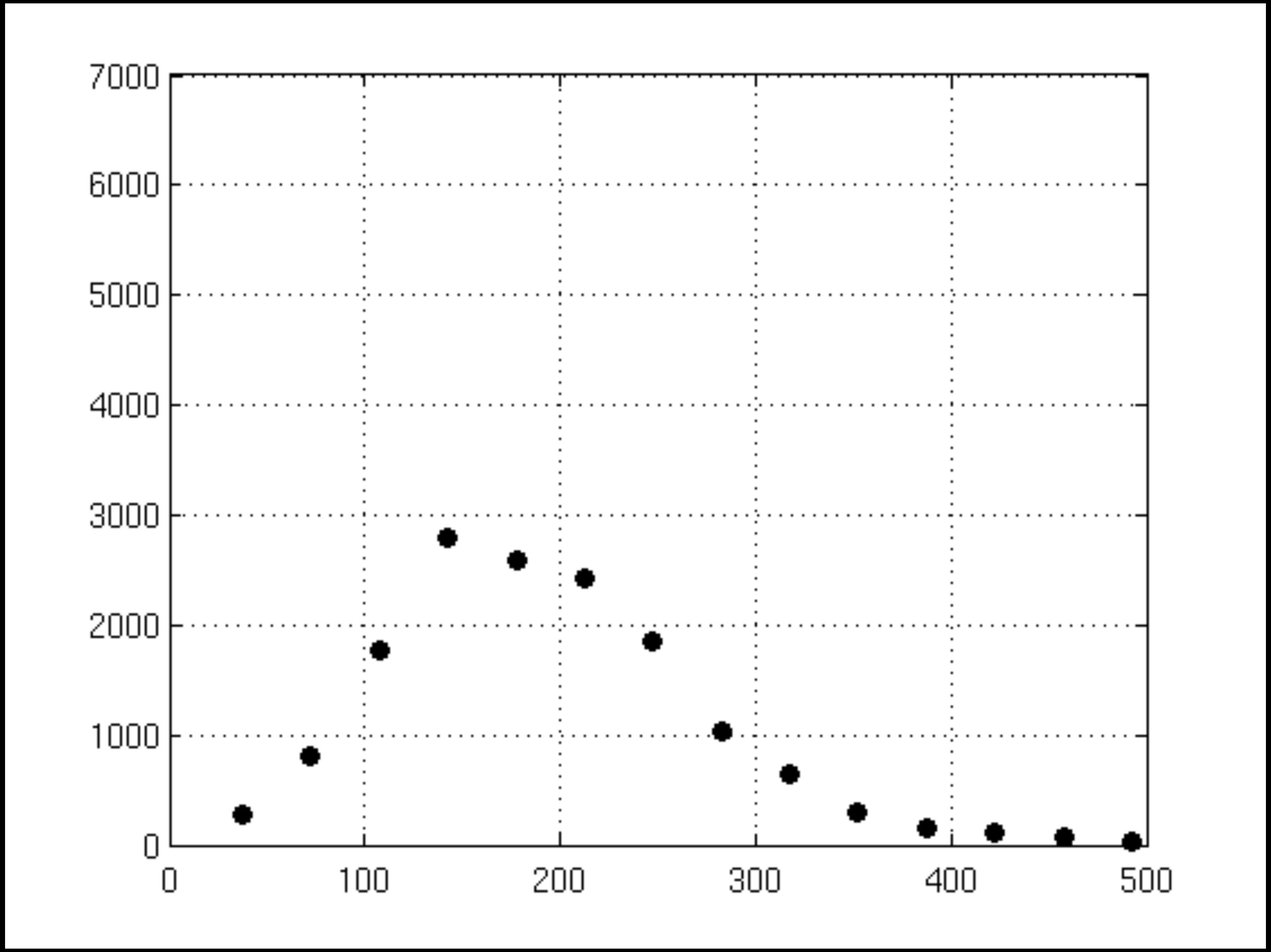


Monte Carlo analysis

Noise realization 0001



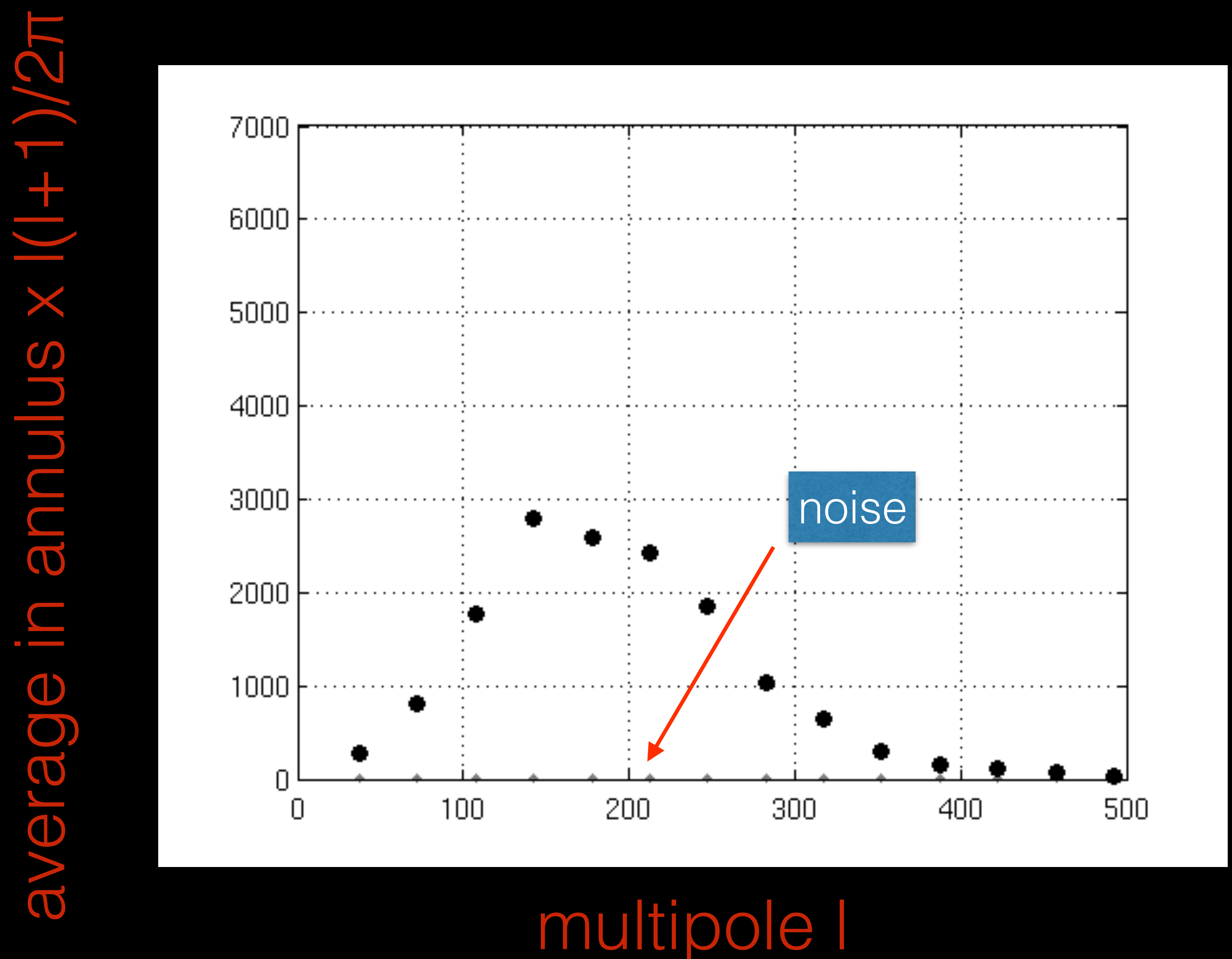
Monte Carlo analysis



average in annulus x l(l+1)/2π

multipole l

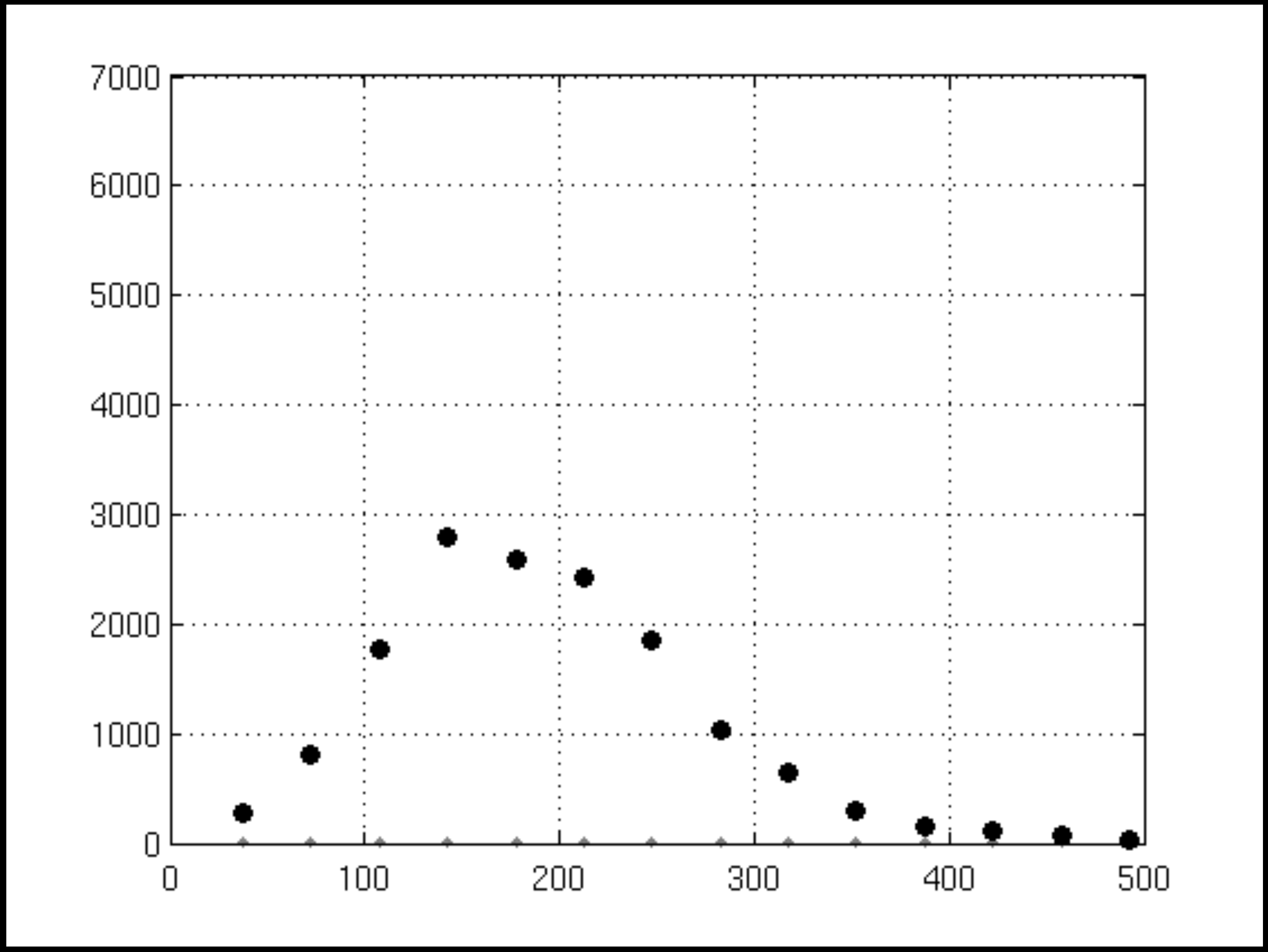
Monte Carlo analysis



This is a ridiculously significant detection of power.

Let’s just assume for the moment it’s not instrumental systematics. We need to compare to models. Let’s call every cosmologist’s favorite model “LCDM”

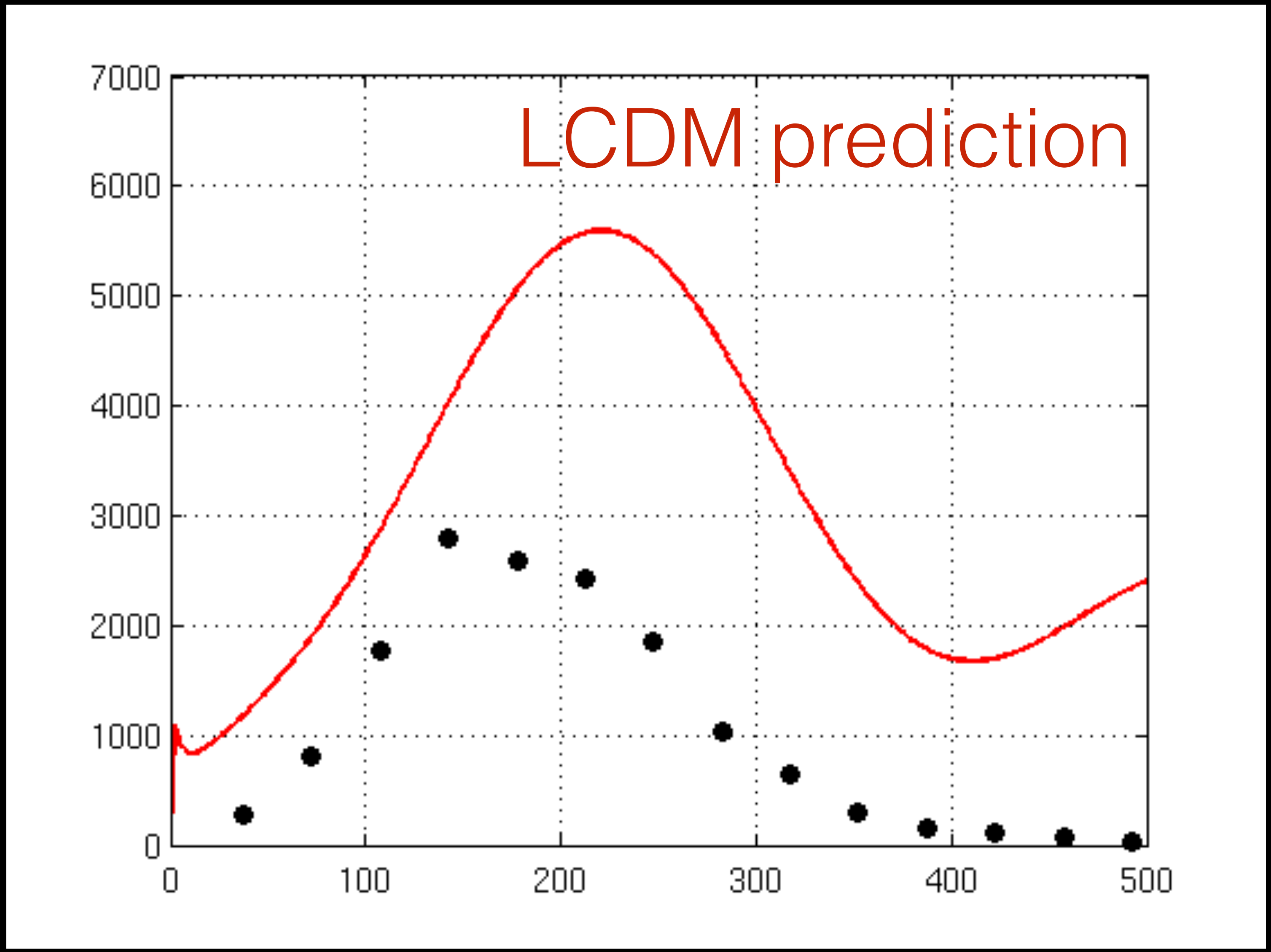
Monte Carlo analysis



average in annulus x l(l+1)/2π

multipole l

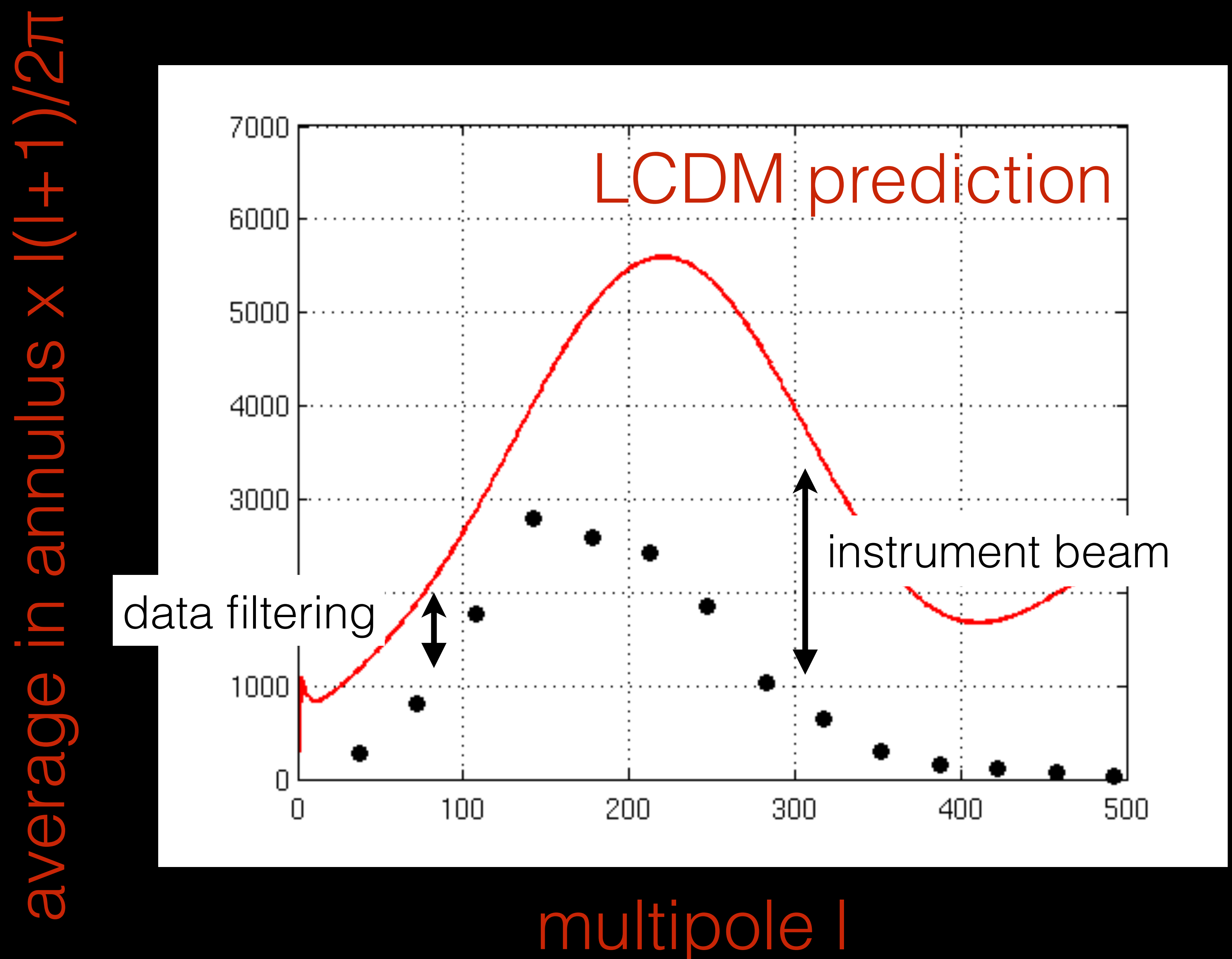
Monte Carlo analysis



average in annulus x l(l+1)/2π

multipole l

Monte Carlo analysis

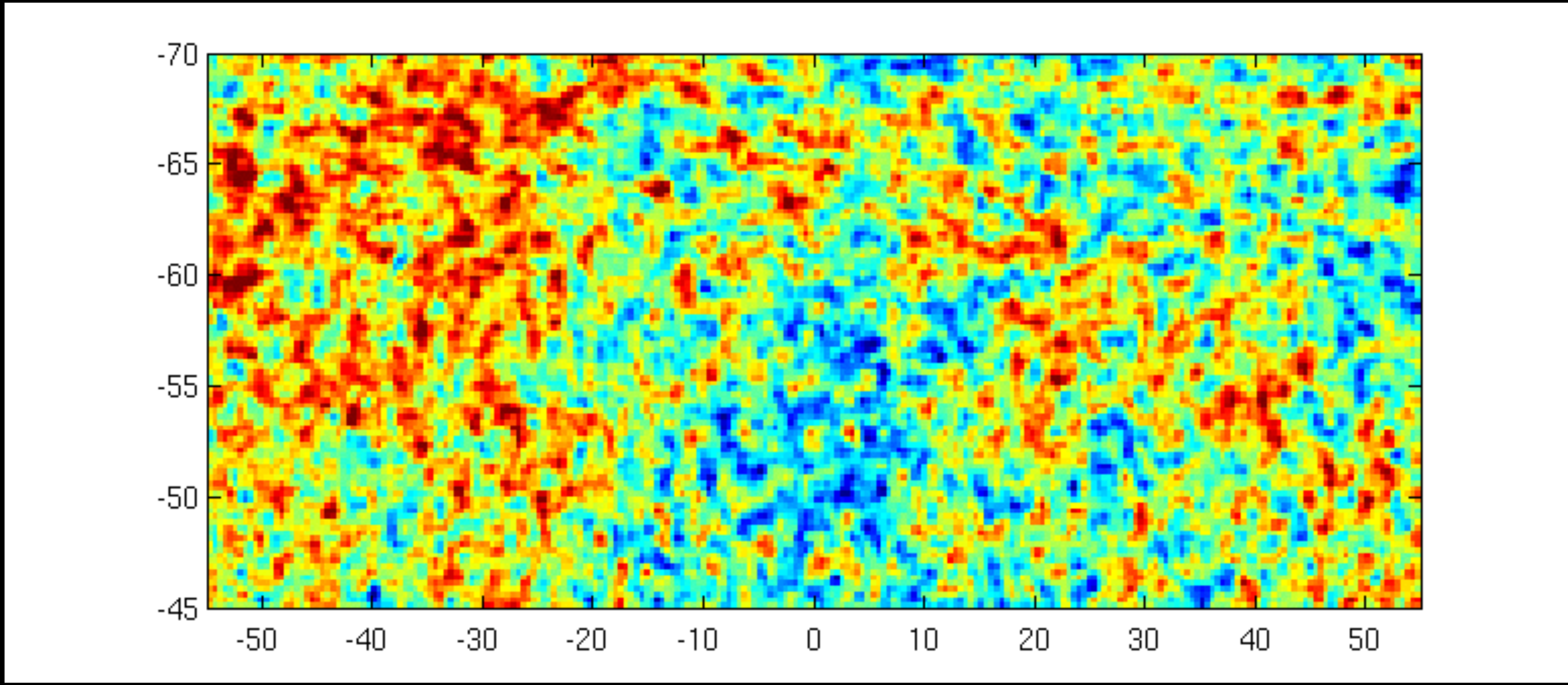


We must model the effect of the instrument.

One way to do this is to create noiseless simulated input realizations and pass it them through the same data reduction pipeline that the real data uses.

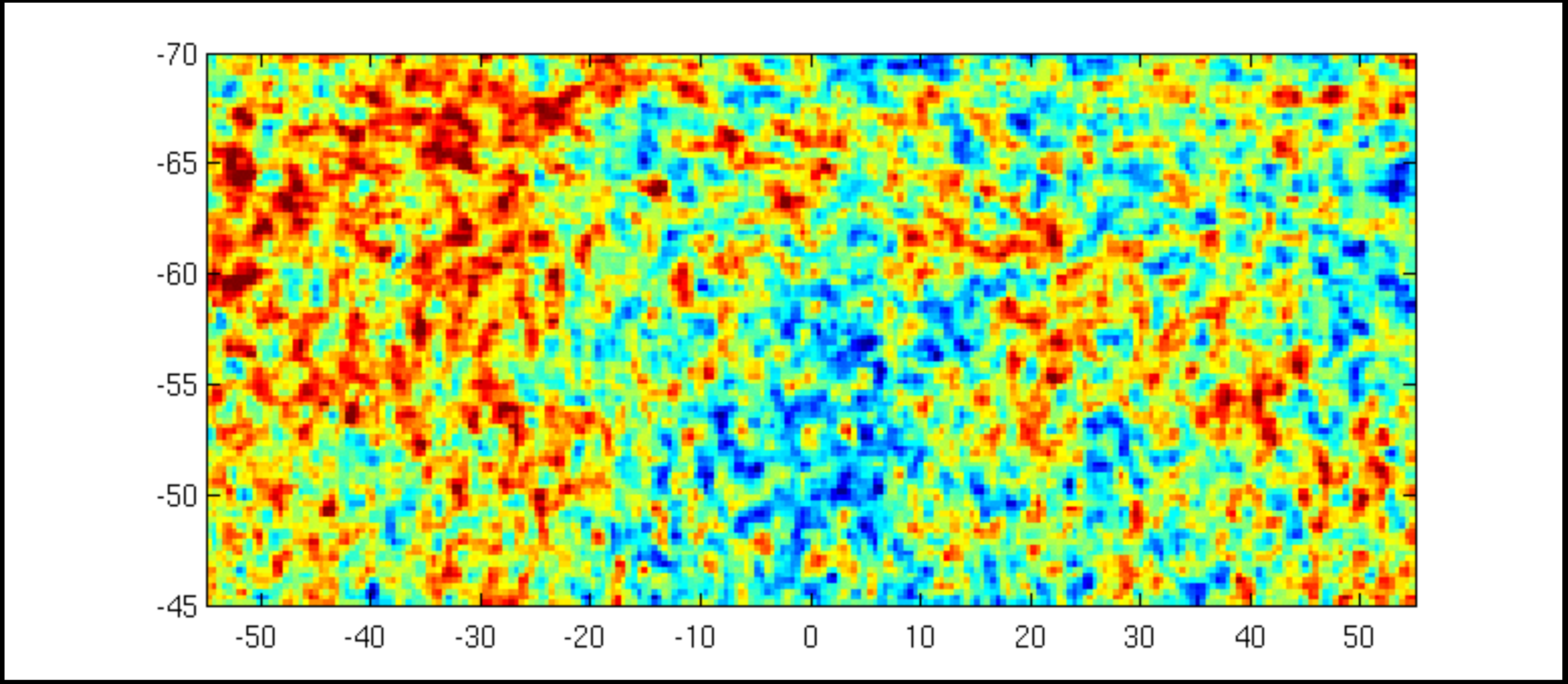
Monte Carlo analysis

Signal realization 0001



Monte Carlo analysis

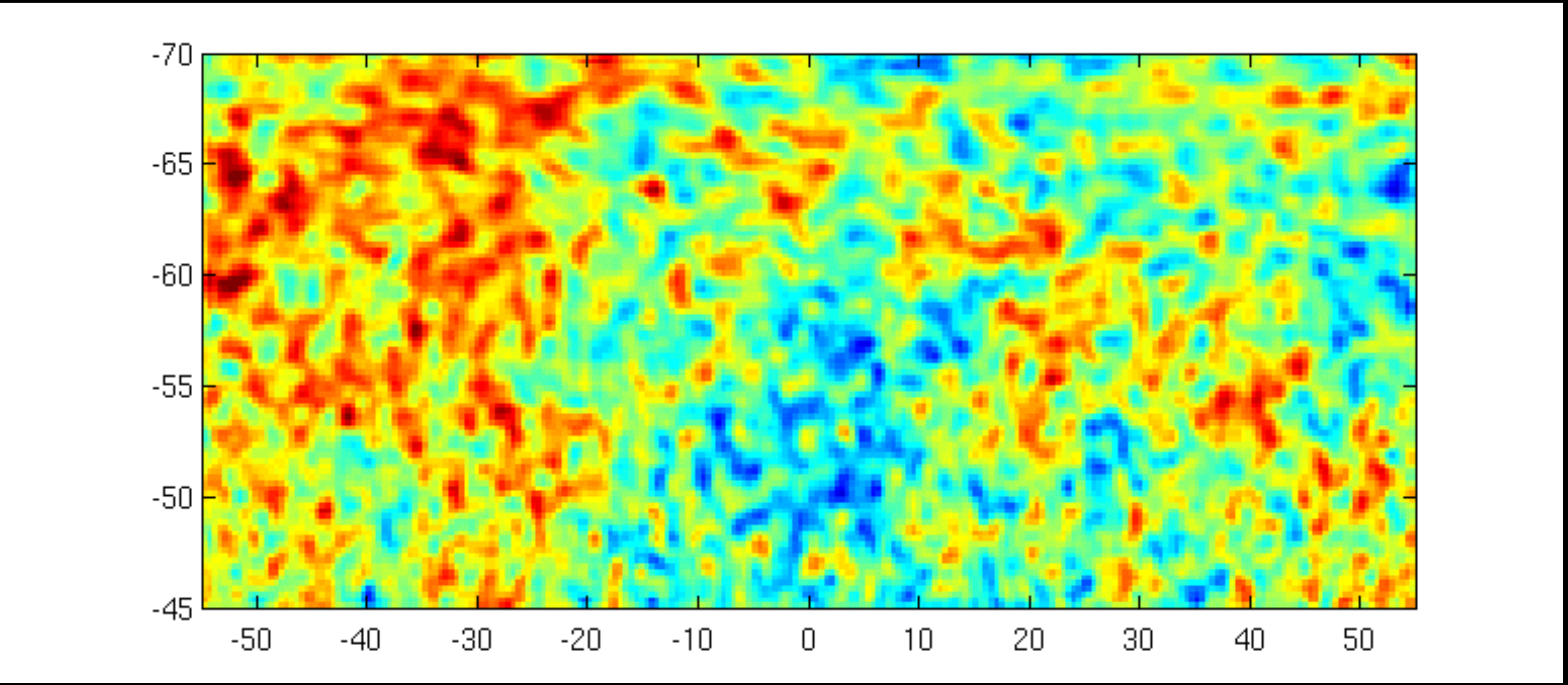
Signal realization 0001



Generate random Gaussian numbers whose underlying power spectrum matches the fiducial theory spectrum.

Monte Carlo analysis

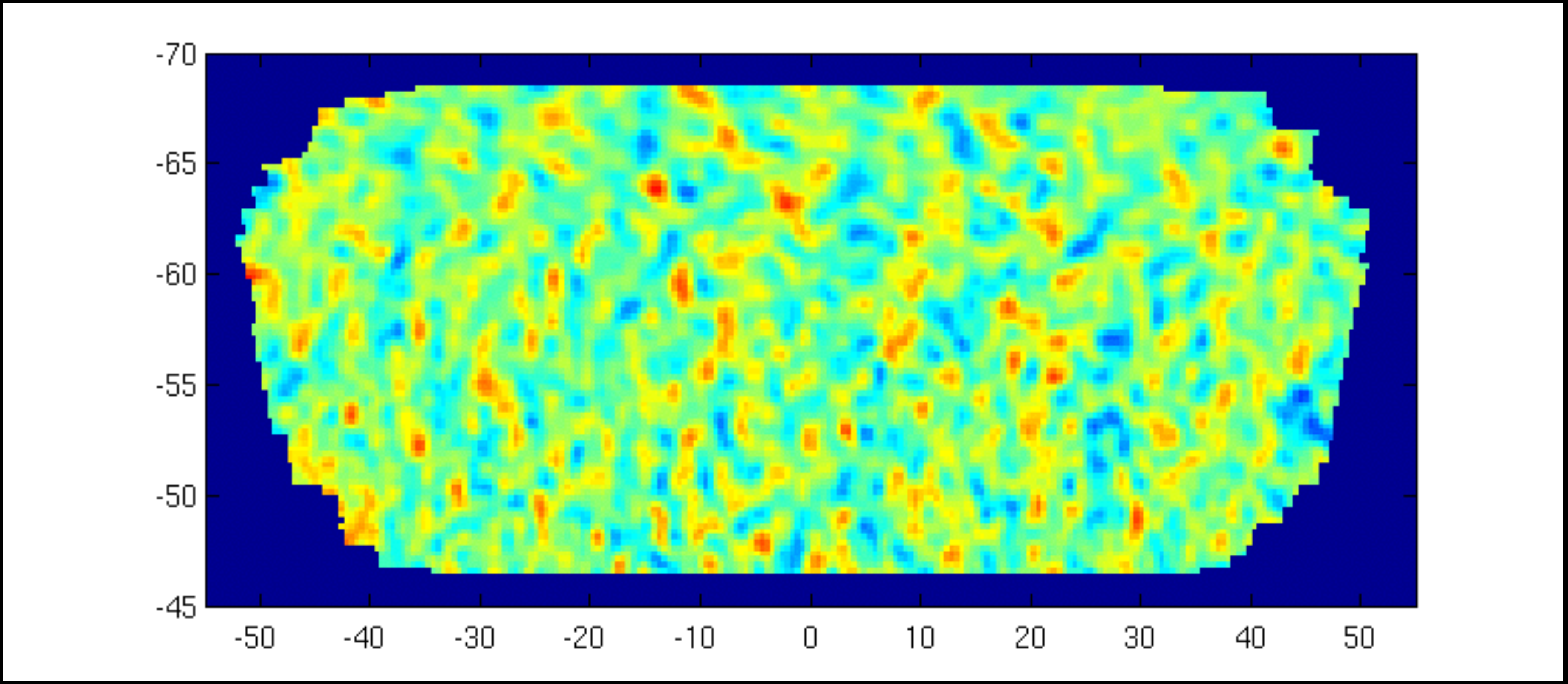
Signal realization 0001



Now convolve the input map with by the instrument's angular response pattern (i.e. "beam" or "point spread function")

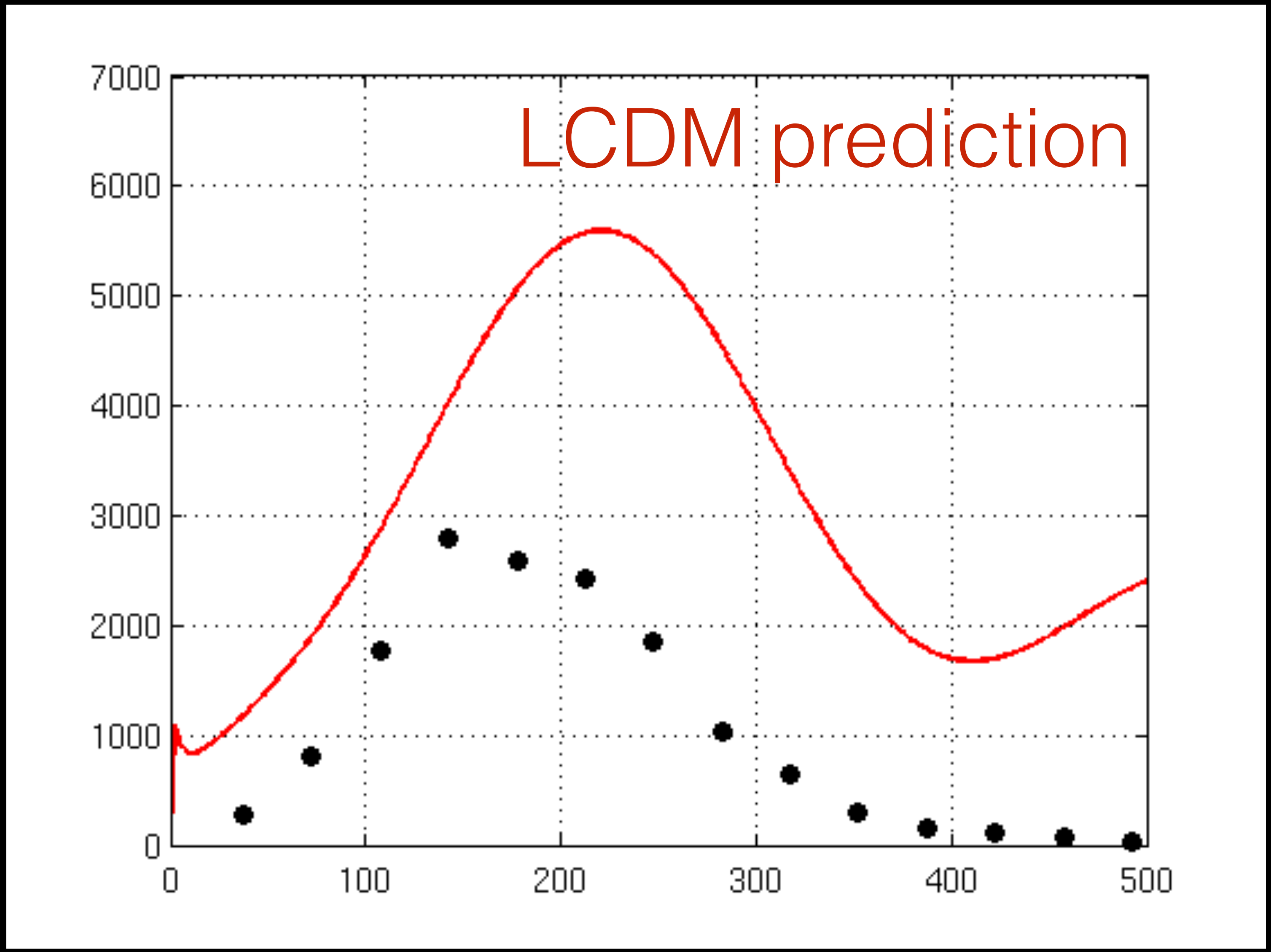
Monte Carlo analysis

Signal realization 0001



Now pass through the same data reduction pipeline as the real data. This imposes the same filtering on the simulation as on the data.

Monte Carlo analysis

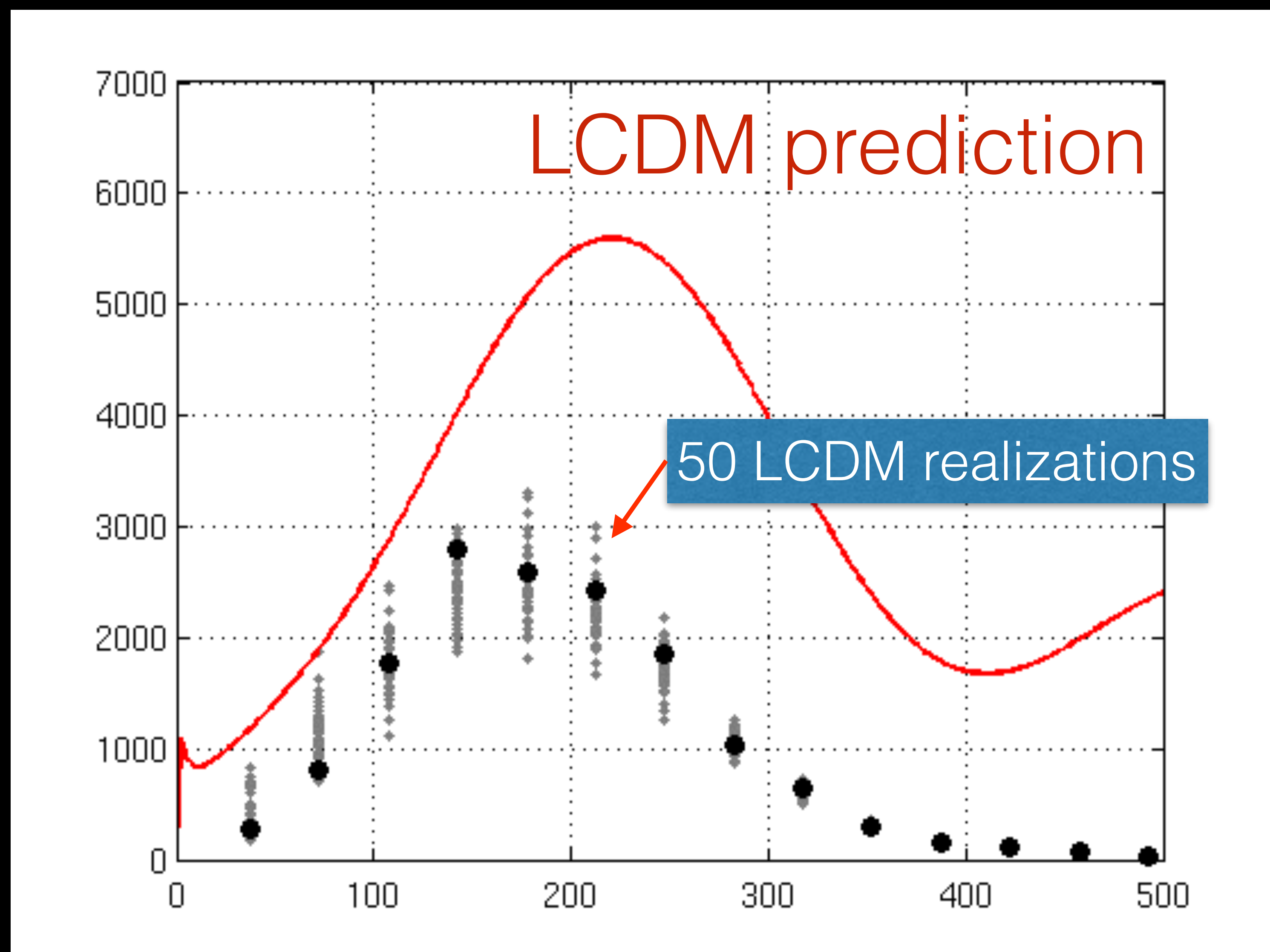


average in annulus x l(l+1)/2π

multipole l

Monte Carlo analysis

average in annulus x l(l+1)/2π



multipole l

Monte Carlo analysis

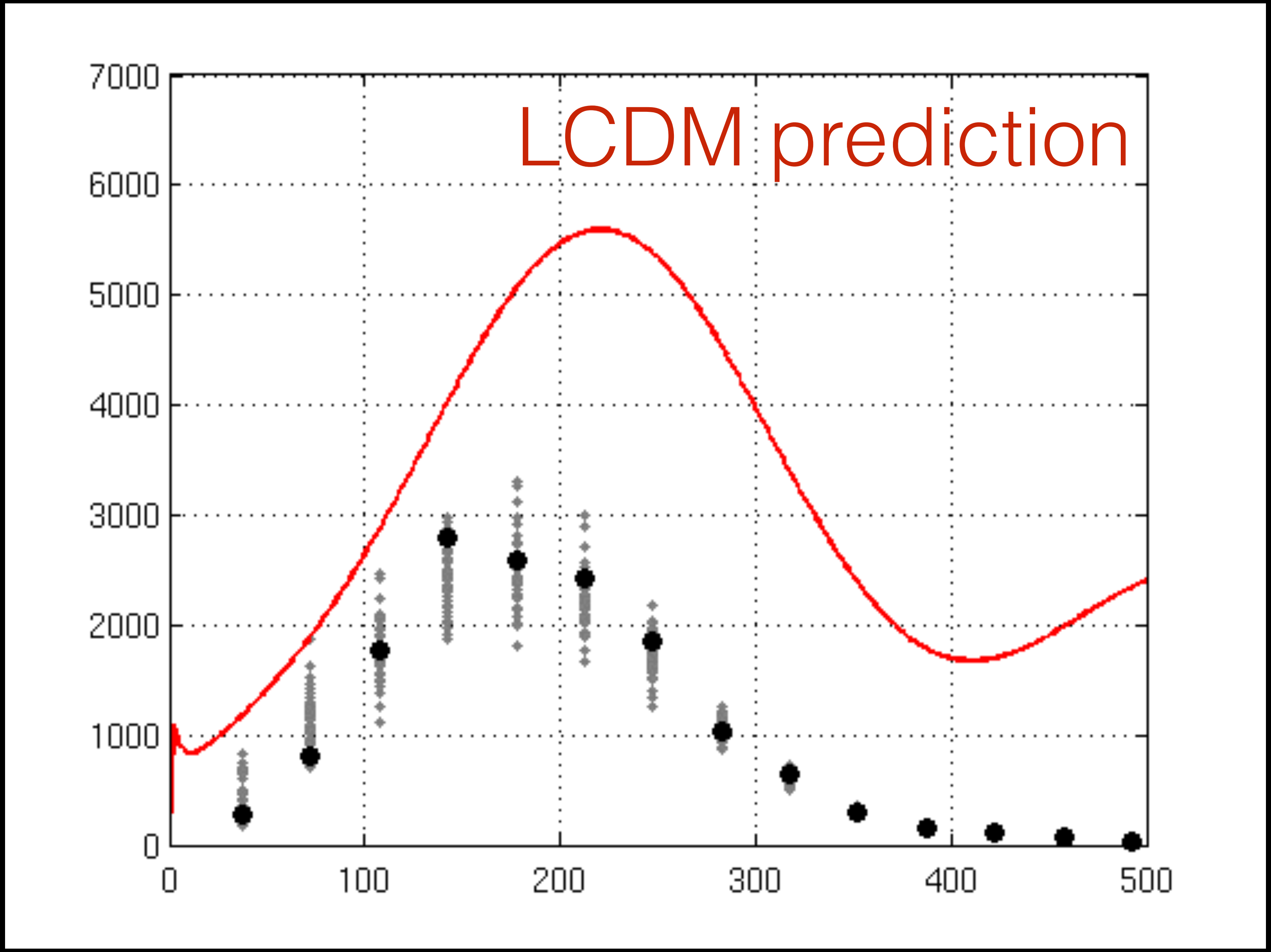
The spread in the simulations is so-called “cosmic variance”, which enters the Monte Carlo analysis as different random realizations for the original input map.

Monte Carlo analysis

Remove the mean effect of power suppression by dividing both the real data and the simulations by the mean of the signal simulations.

(The analysis insensitive to the choice of fiducial model.)

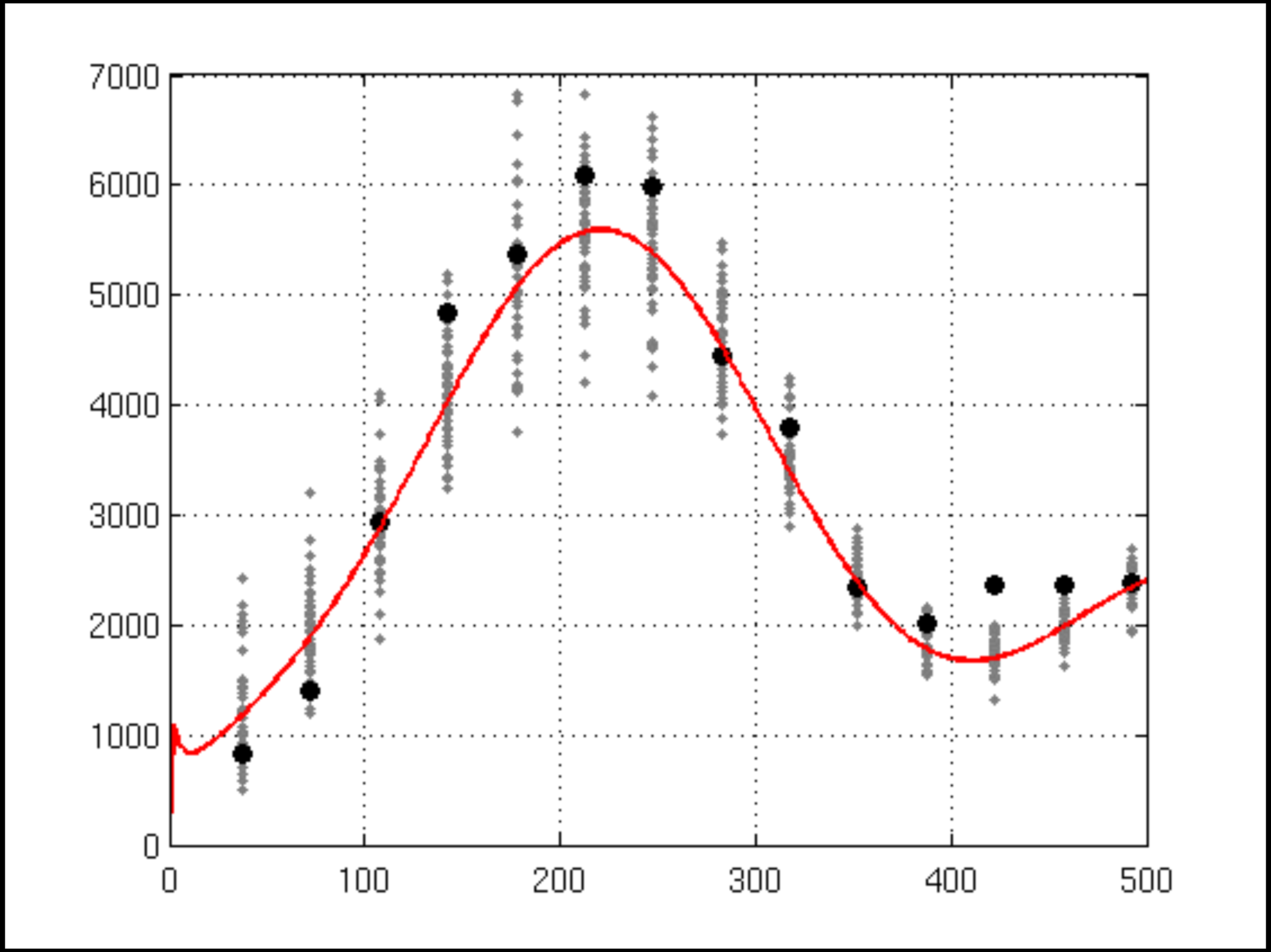
Monte Carlo analysis



average in annulus x l(l+1)/2π

multipole l

Monte Carlo analysis



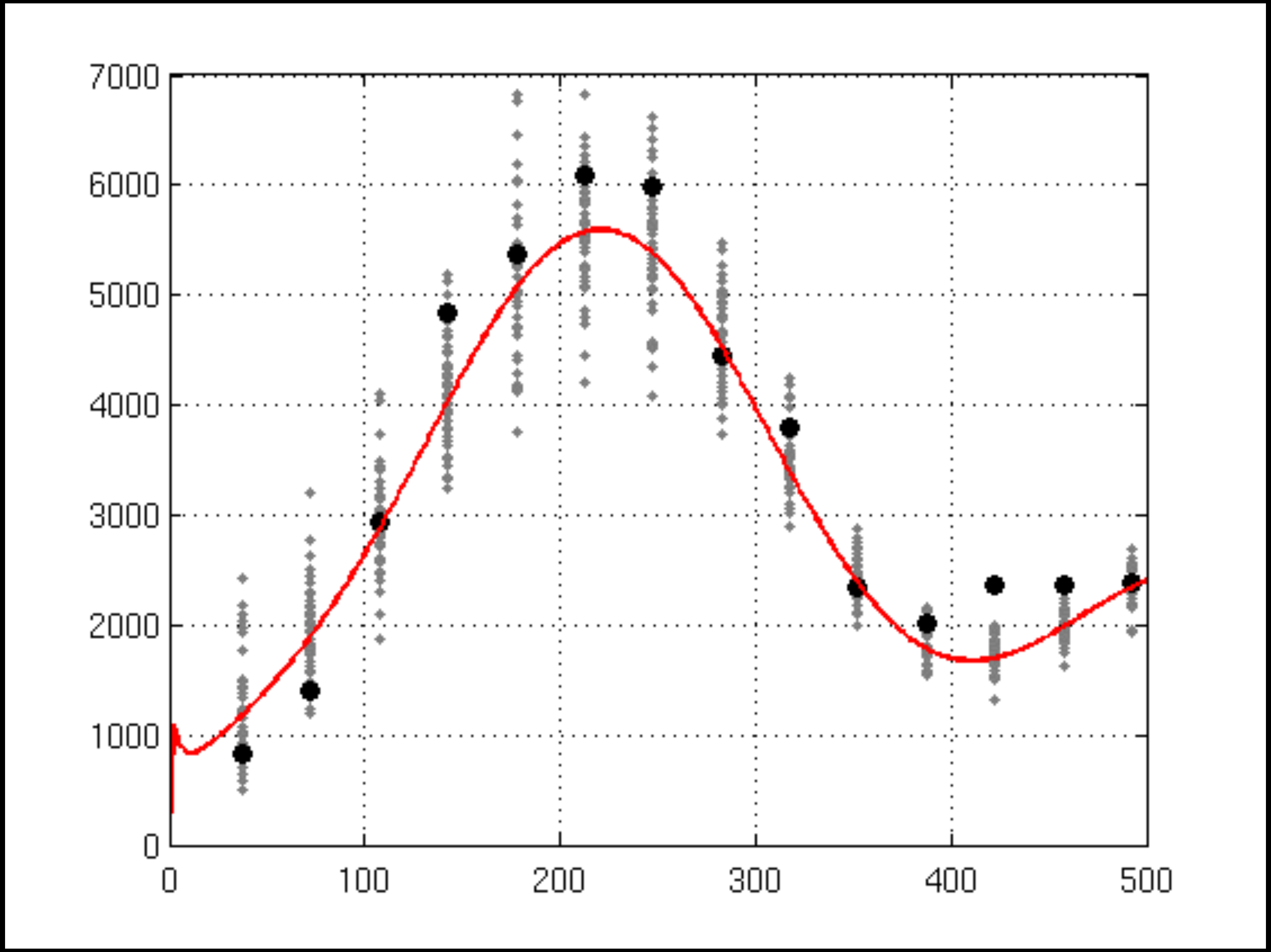
average in annulus x l(l+1)/2π

multipole l

Monte Carlo analysis

Replace the simulations with error bars equal to their standard deviation, centered on the real data points

Monte Carlo analysis

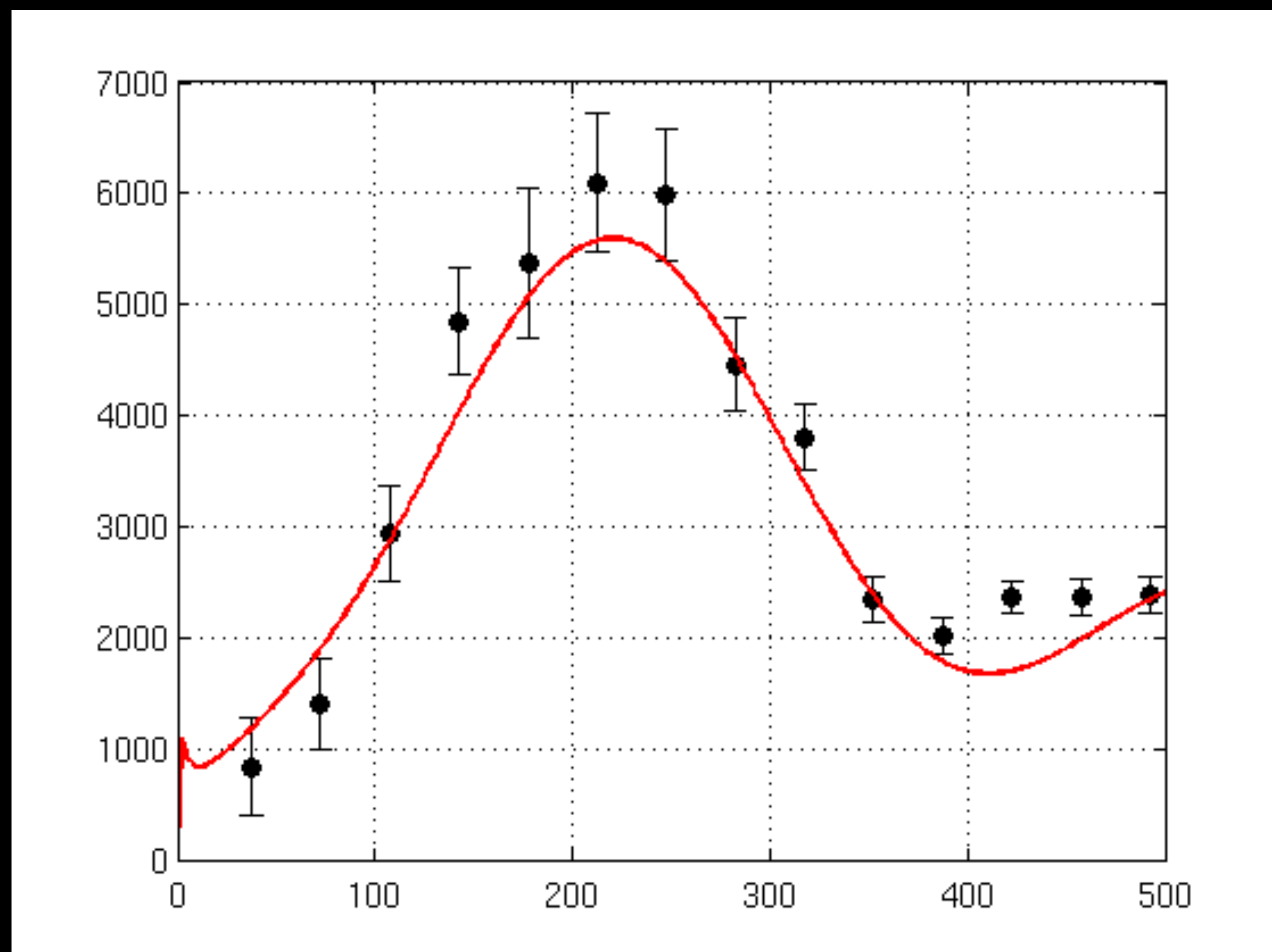


average in annulus x l(l+1)/2π

multipole l

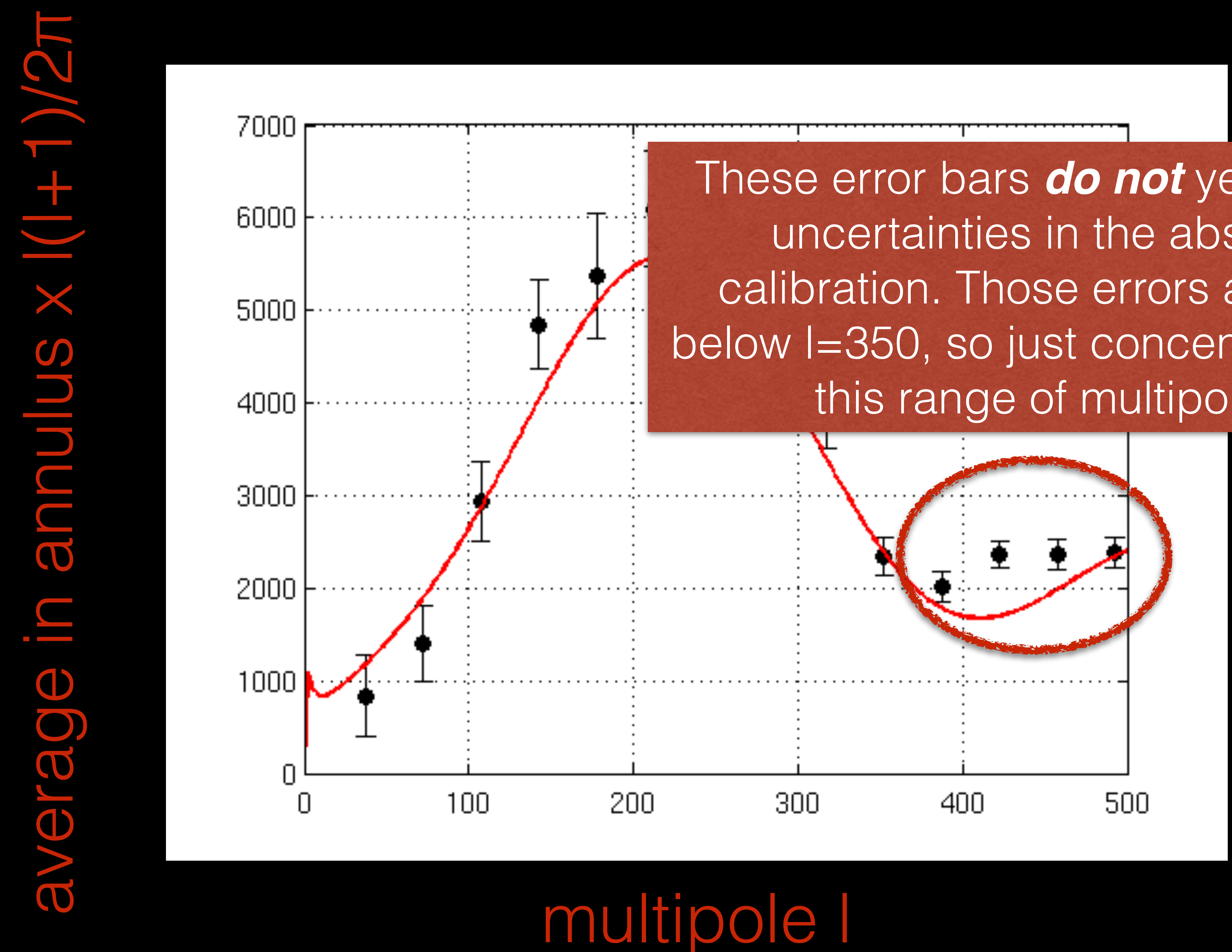
Monte Carlo analysis

average in annulus x l(l+1)/2π



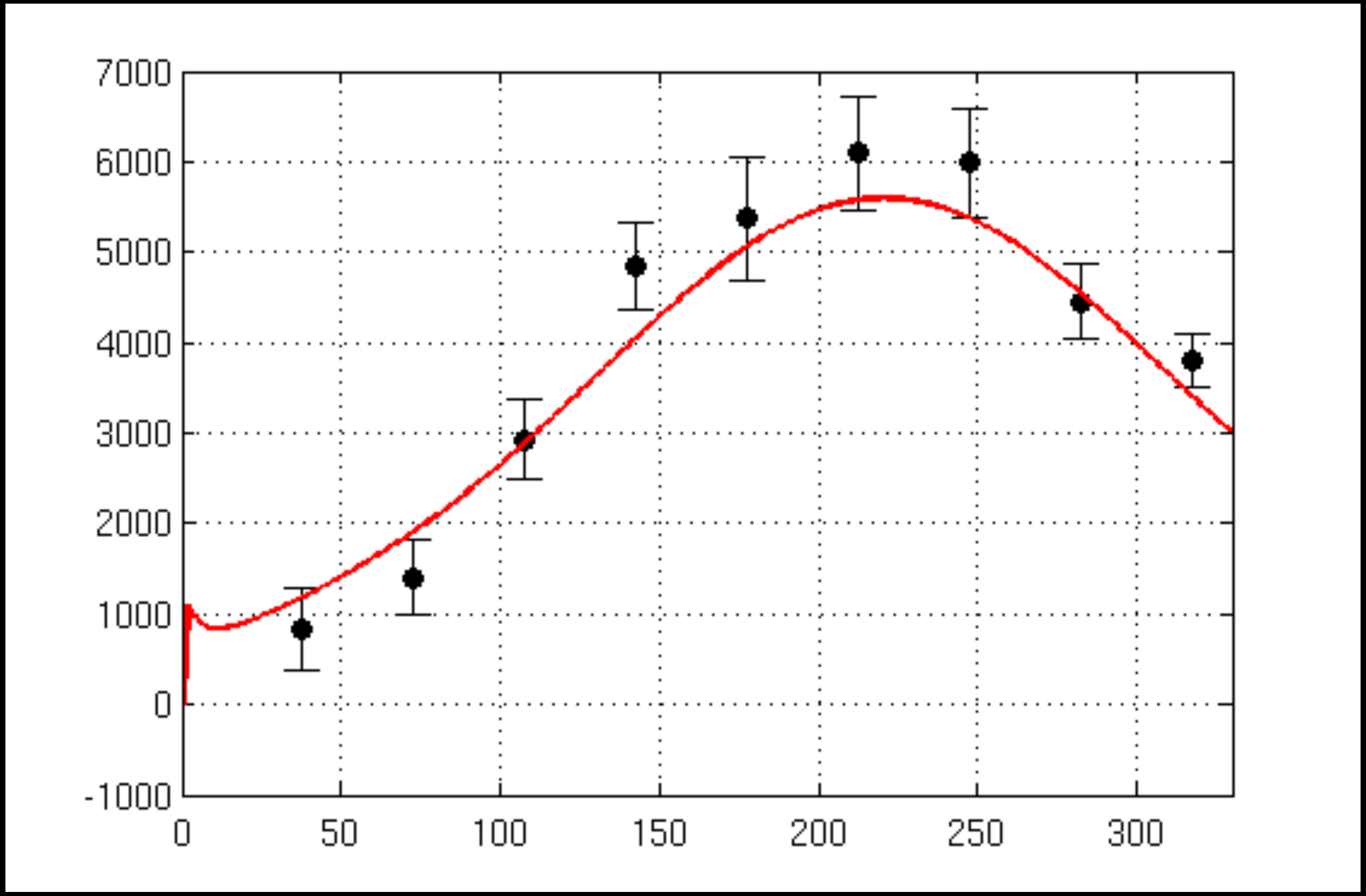
multipole l

Monte Carlo analysis



These error bars ***do not*** yet contain uncertainties in the absolute calibration. Those errors are <1% below l=350, so just concentrate on in this range of multipoles.

Monte Carlo analysis



average in annulus x l(l+1)/2π

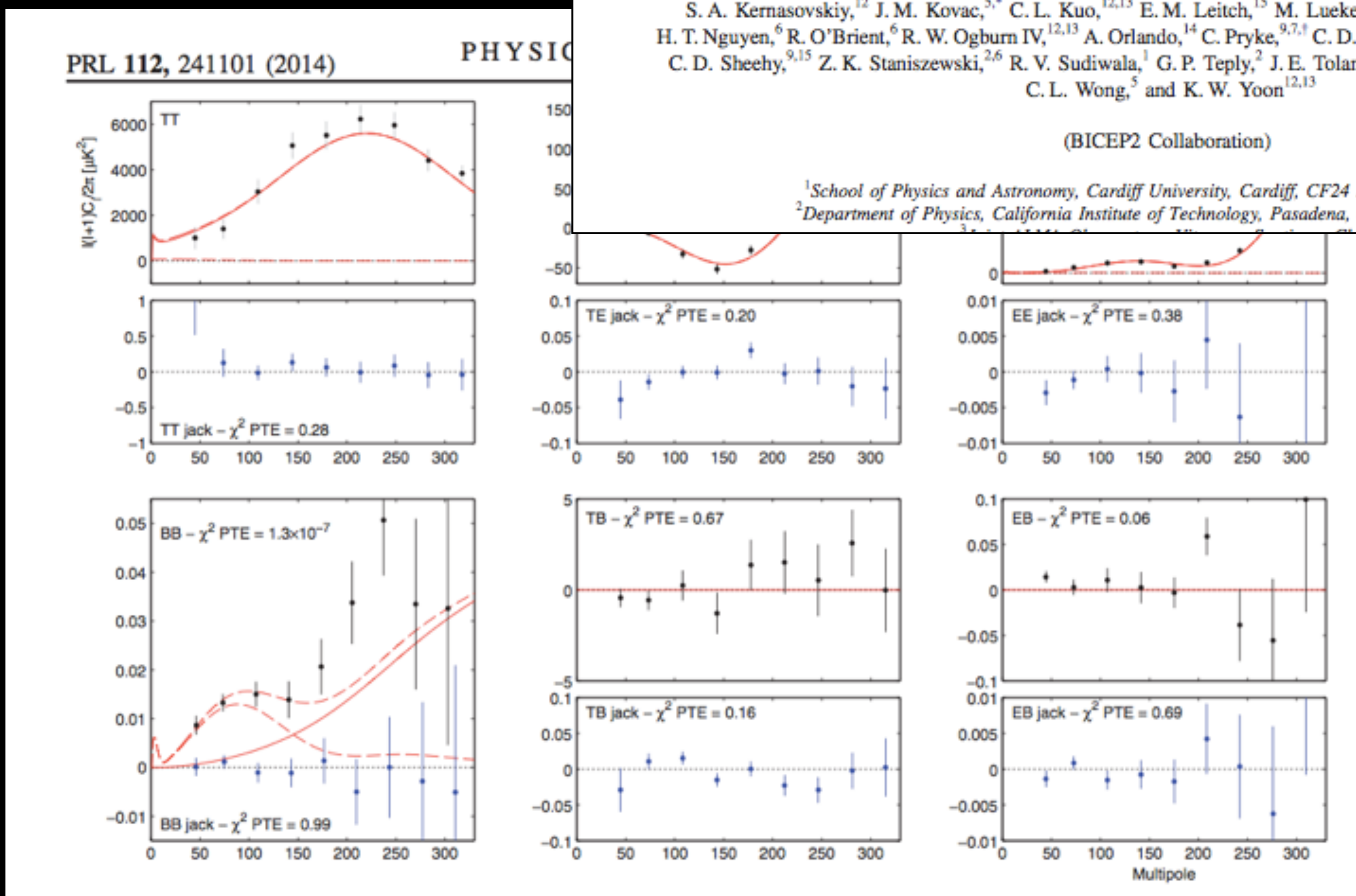
multipole l

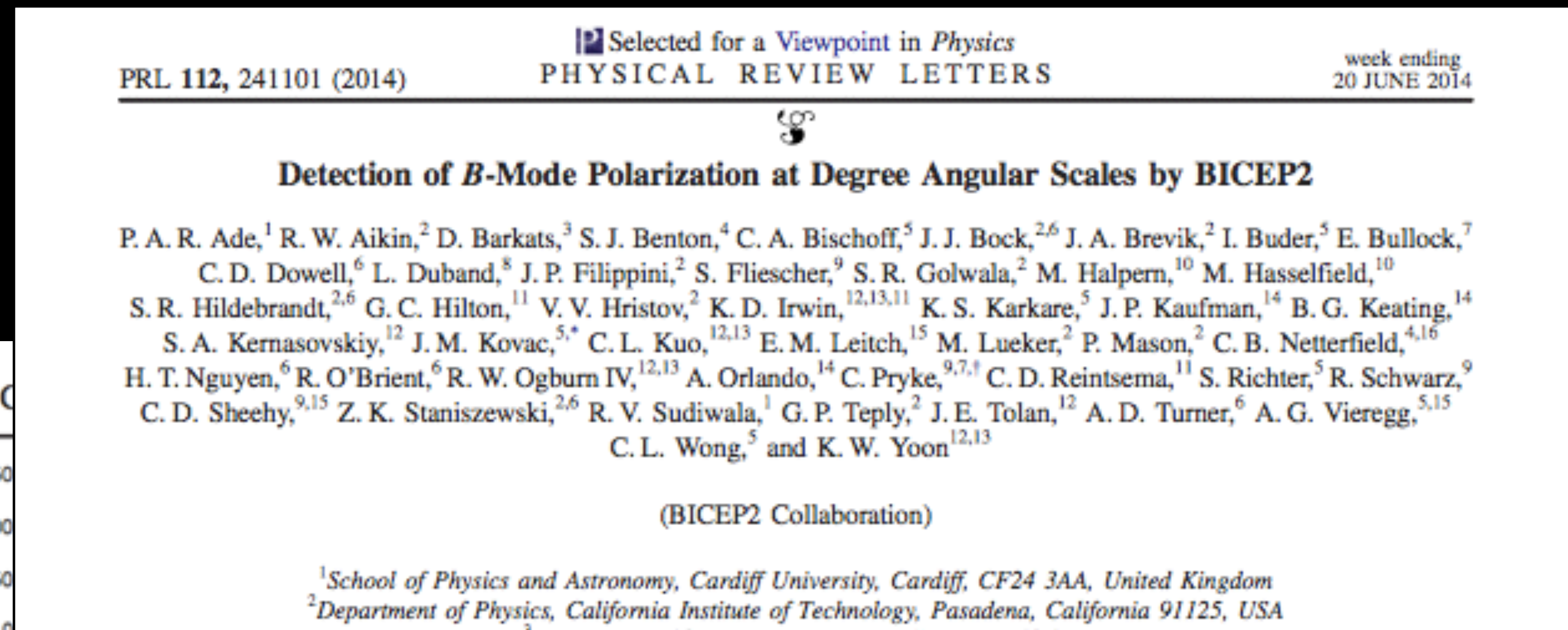
Monte Carlo analysis

If you can demonstrate you don't have to worry about instrumental systematics, derive some model parameter likelihoods and publish.

Revisit models as necessary, but the data points and uncertainties stand.

Monte Carlo analysis





Selected for a Viewpoint in *Physics*

PRL **112,** 241101 (2014) PHYSICAL REVIEW LETTERS week ending 20 JUNE 2014

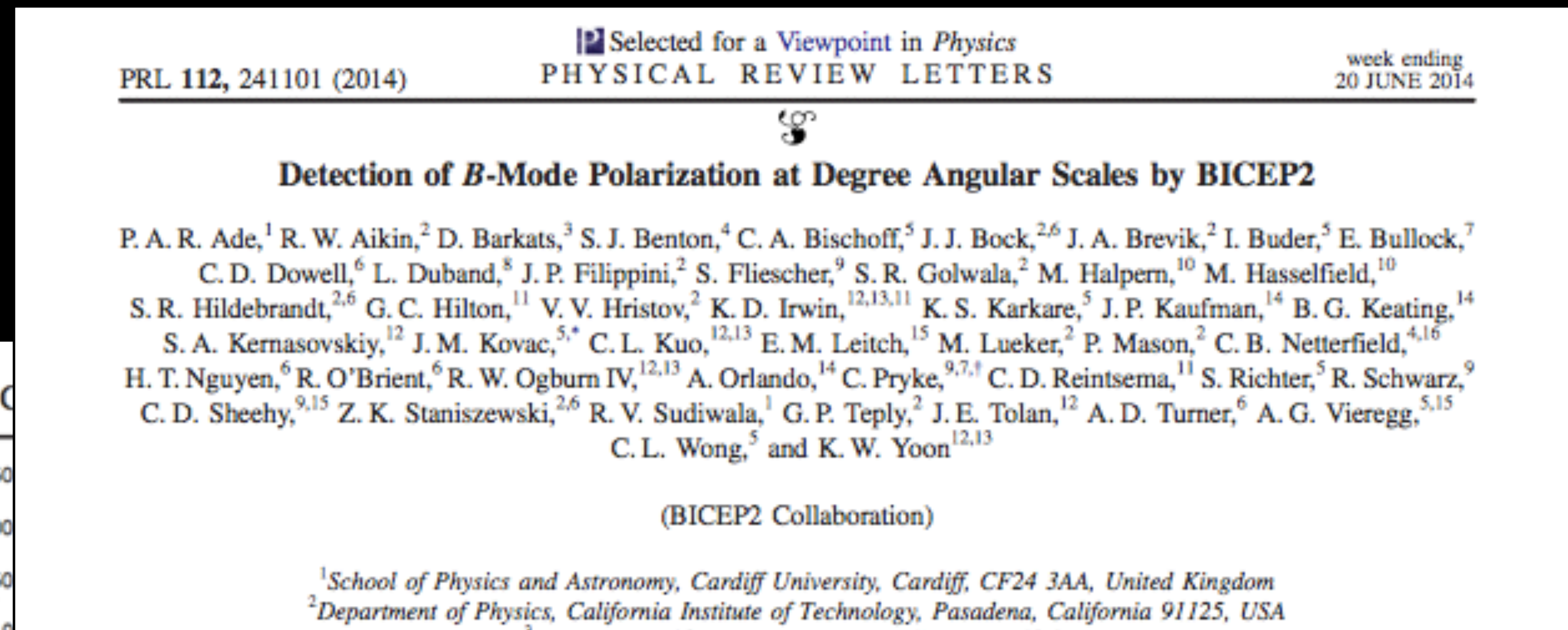
Detection of *B*-Mode Polarization at Degree Angular Scales by BICEP2

P. A. R. Ade,[1] R. W. Aikin,[2] D. Barkats,[3] S. J. Benton,[4] C. A. Bischoff,[5] J. J. Bock,[2,6] J. A. Brevik,[2] I. Buder,[5] E. Bullock,[7] C. D. Dowell,[6] L. Duband,[8] J. P. Filippini,[2] S. Fliescher,[9] S. R. Golwala,[2] M. Halpern,[10] M. Hasselfield,[10] S. R. Hildebrandt,[2,6] G. C. Hilton,[11] V. V. Hristov,[2] K. D. Irwin,[12,13,11] K. S. Karkare,[5] J. P. Kaufman,[14] B. G. Keating,[14] S. A. Kernasovskiy,[12] J. M. Kovac,[5,*] C. L. Kuo,[12,13] E. M. Leitch,[15] M. Lueker,[2] P. Mason,[2] C. B. Netterfield,[4,16] H. T. Nguyen,[6] R. O'Brient,[6] R. W. Ogburn IV,[12,13] A. Orlando,[14] C. Pryke,[9,7,†] C. D. Reintsema,[11] S. Richter,[5] R. Schwarz,[9] C. D. Sheehy,[9,15] Z. K. Staniszewski,[2,6] R. V. Sudiwala,[1] G. P. Teply,[2] J. E. Tolan,[12] A. D. Turner,[6] A. G. Vieregg,[5,15] C. L. Wong,[5] and K. W. Yoon[12,13]

(BICEP2 Collaboration)

[1]*School of Physics and Astronomy, Cardiff University, Cardiff, CF24 3AA, United Kingdom*
[2]*Department of Physics, California Institute of Technology, Pasadena, California 91125, USA*

Monte Carlo analysis



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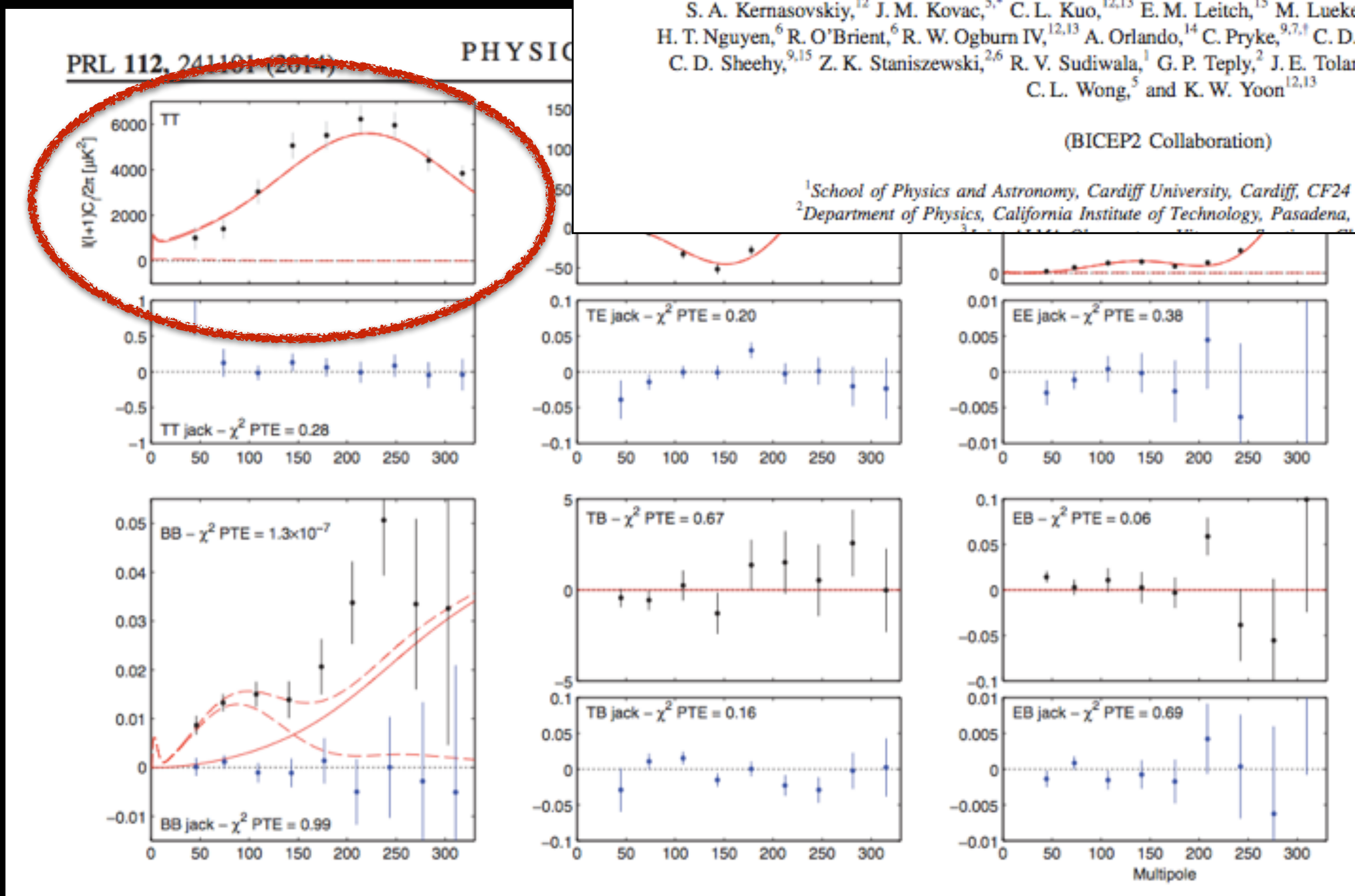
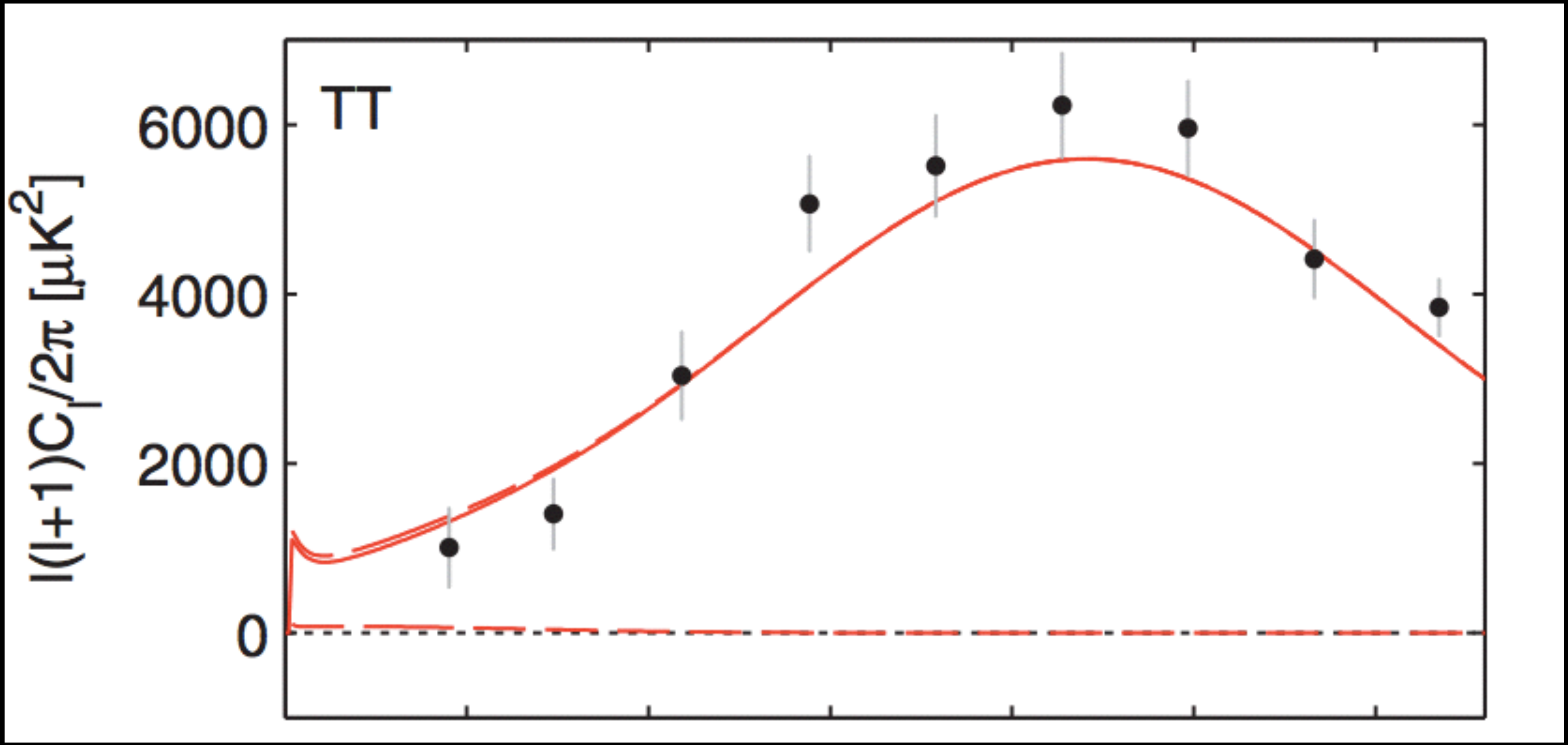
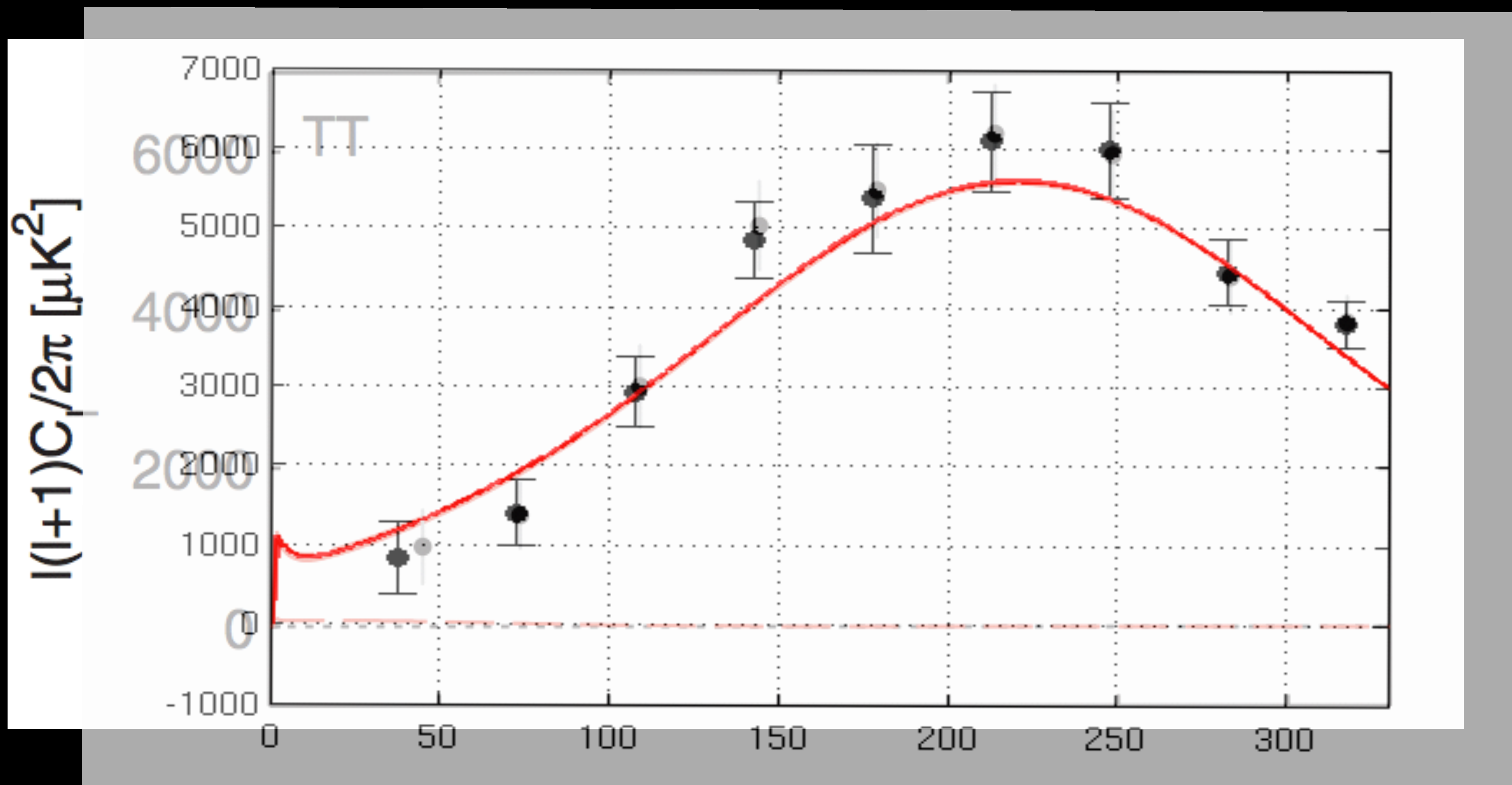


Monte Carlo analysis



Monte Carlo analysis



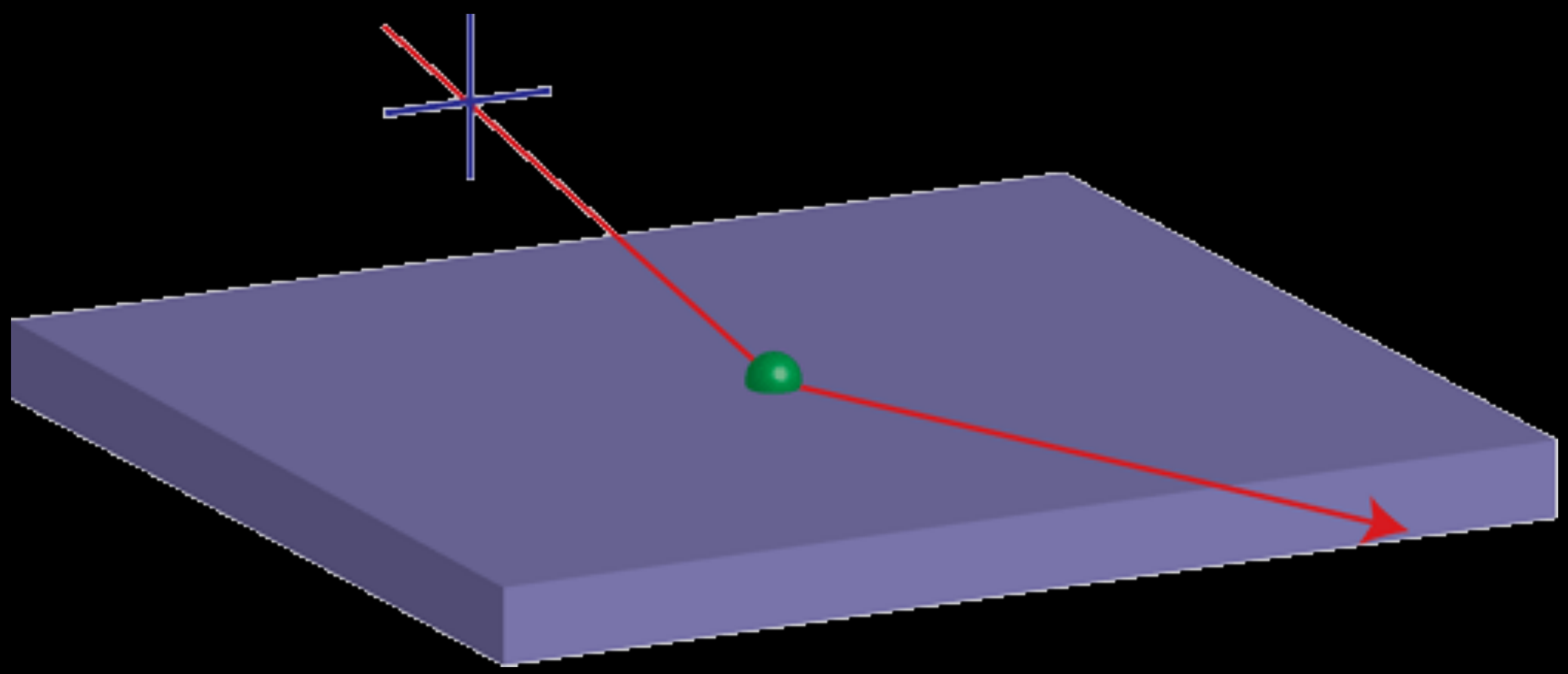
Monte Carlo analysis

There are some subtle differences arising from the fact that this worked example did not include effects of mode mixing, which changes things slightly (for instance the lowest point should not be plotted at the exact bin center like we did), but it’s pretty good!

The CMB is polarized

Generation of polarization by anisotropy

- Heuristically, scattering of light can be thought of as an incoming electric field “shaking” an electron that then re-radiates as a dipole
- Explains polarization of reflected light off a surface because the shaking occurs preferentially in one direction (anisotropy)



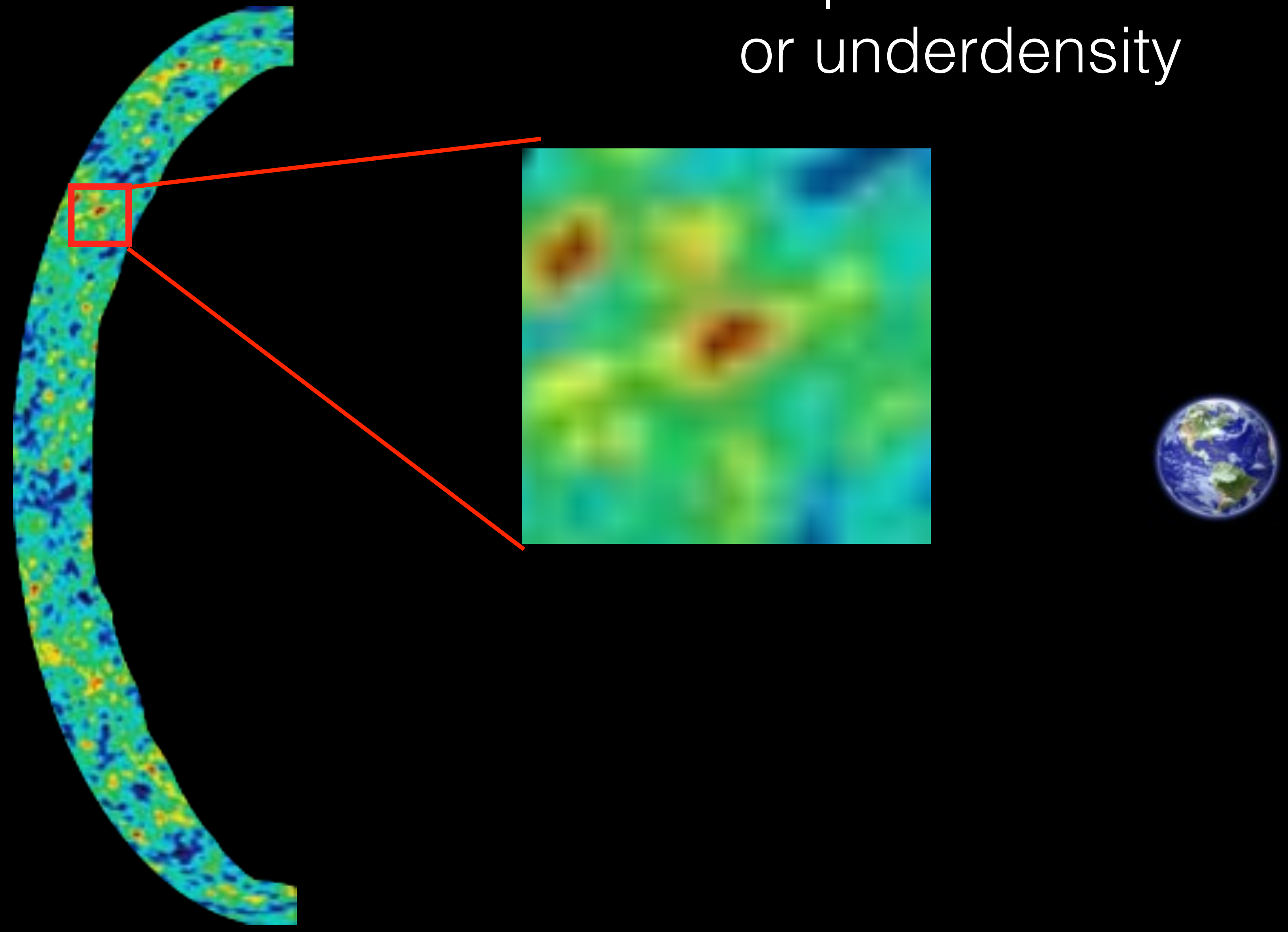
CMB Polarization

The plasma is not stationary.

Motion in the plasma at the time of recombination imparts a small net *polarization* to the photons that scatter off it.

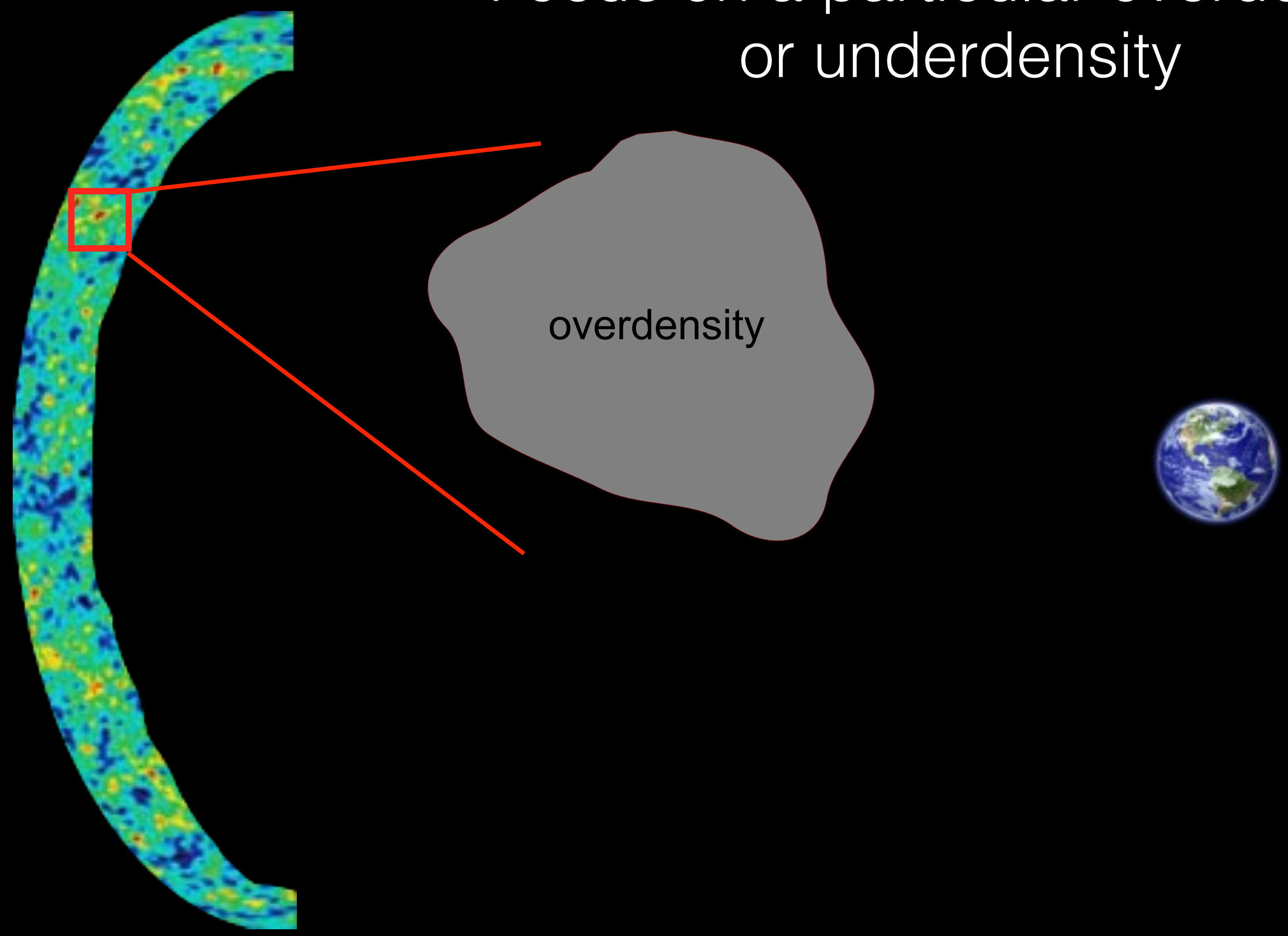
CMB Polarization

Focus on a particular overdensity
or underdensity

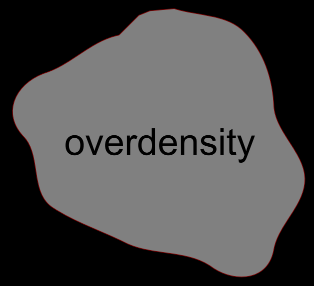


CMB Polarization

Focus on a particular overdensity
or underdensity

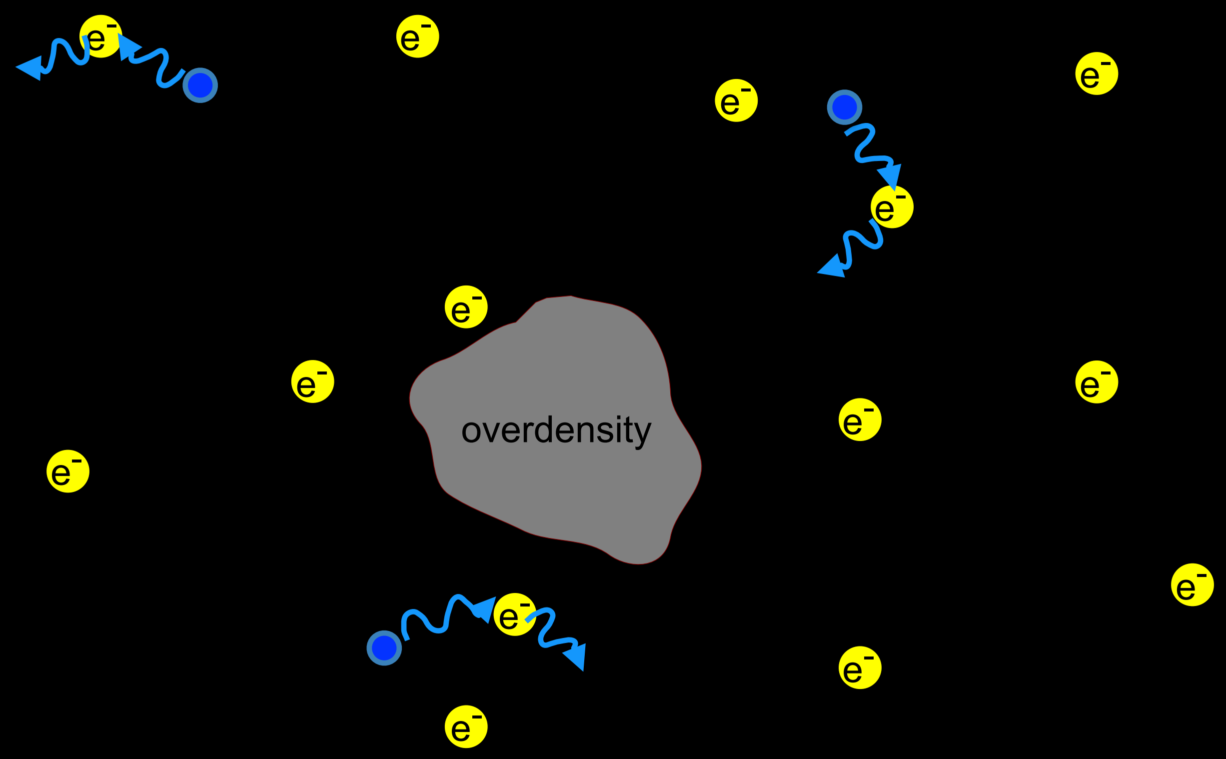


CMB Polarization



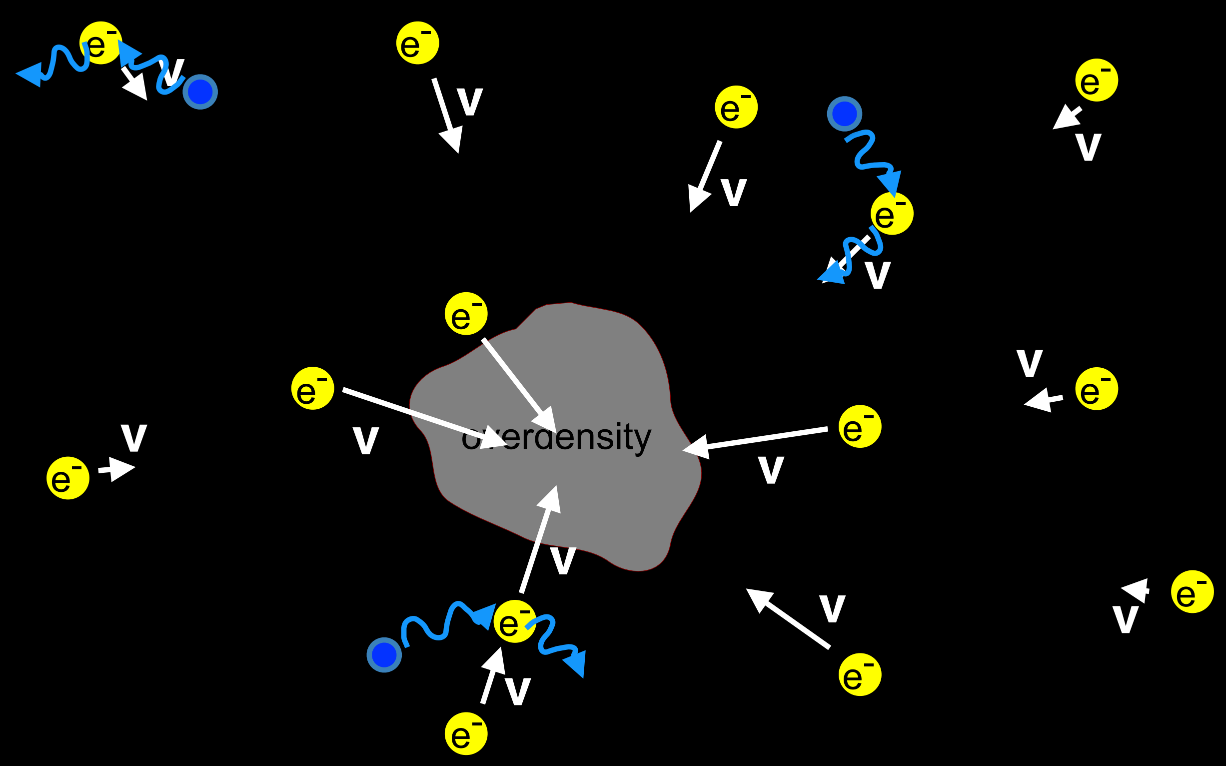
CMB Polarization

A CMB photon we see is one whose last scattering off of a free electron was in the direction of Earth.



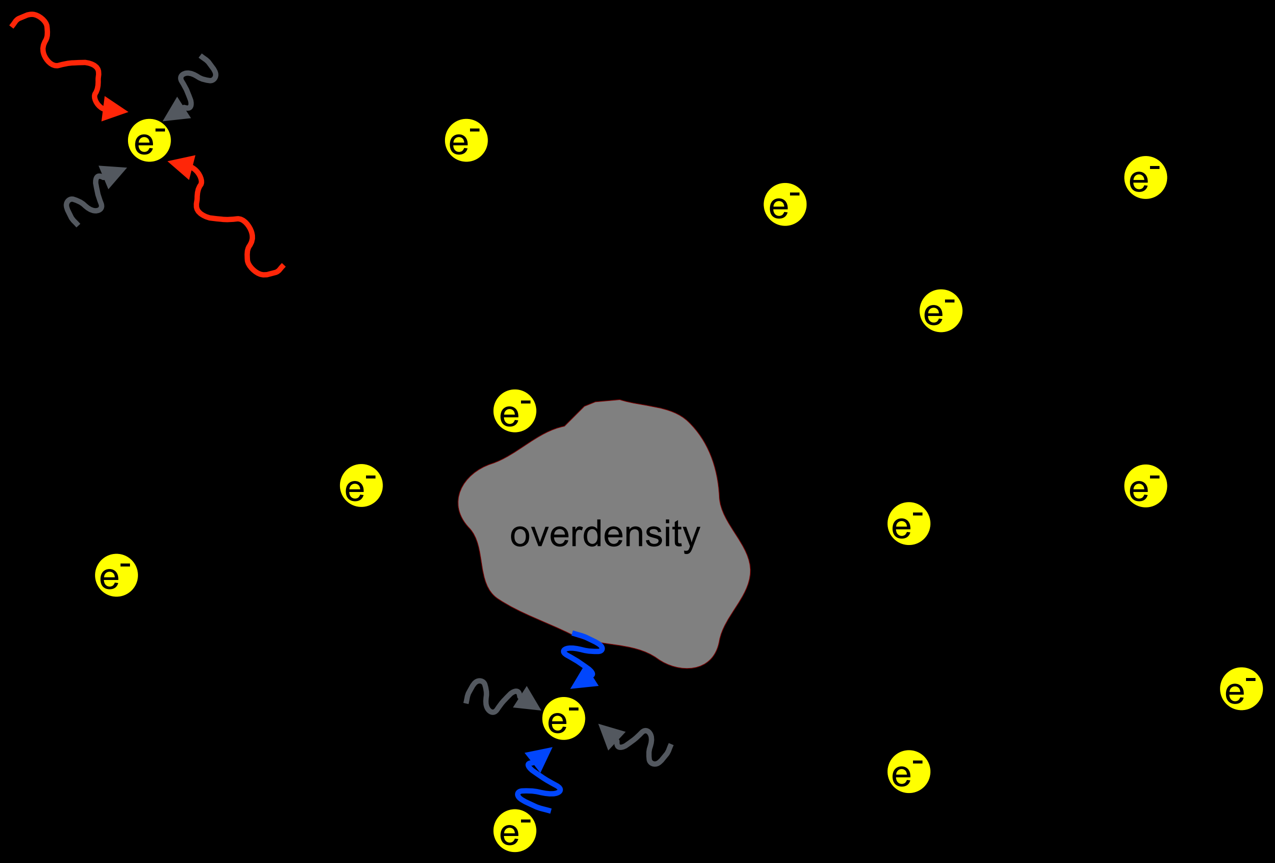
CMB Polarization

The scattering happens in a medium with a bulk velocity flow! There are *gradients* in the velocity field.



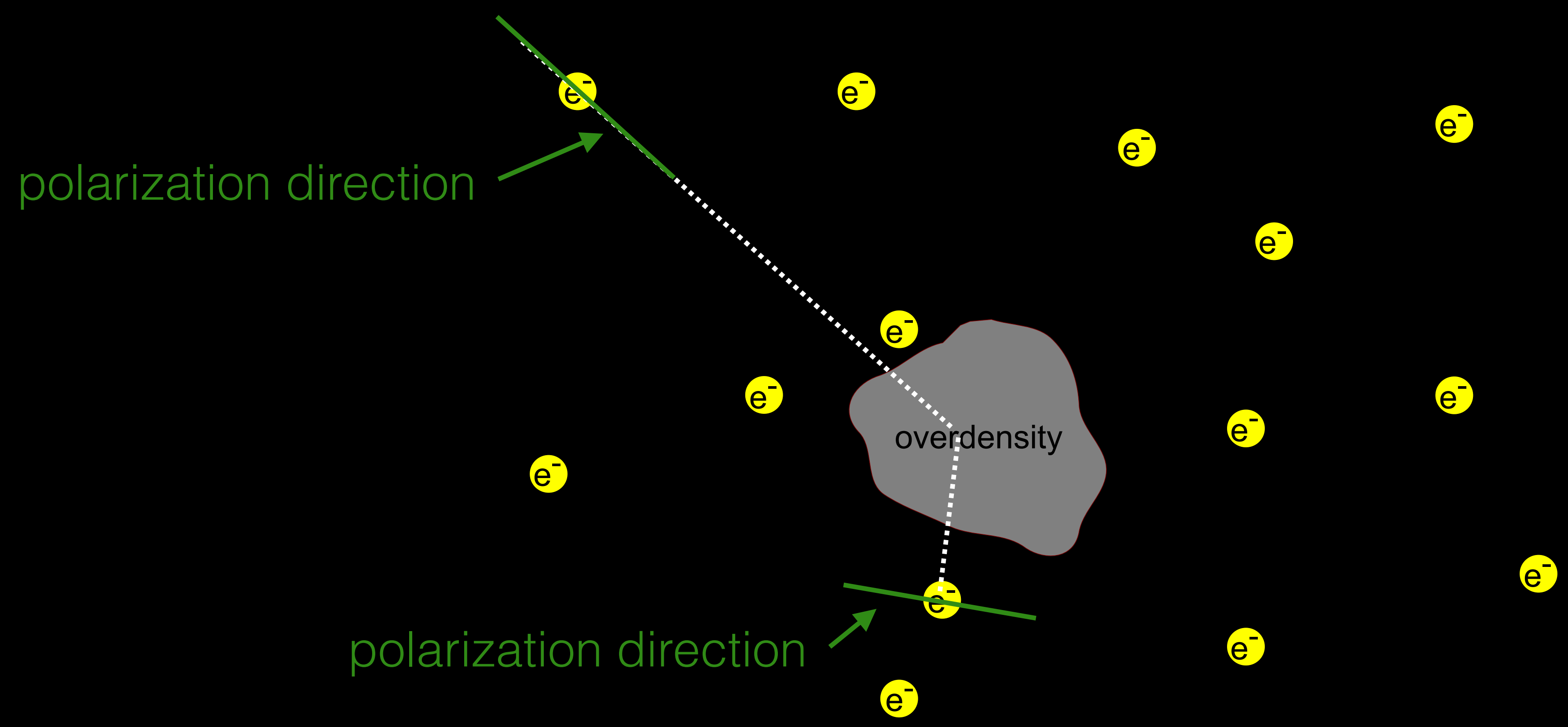
CMB Polarization

In the rest frame of an electron, diverging/converging flow causes redshifting/blueshifting *in the direction of the overdensity*.



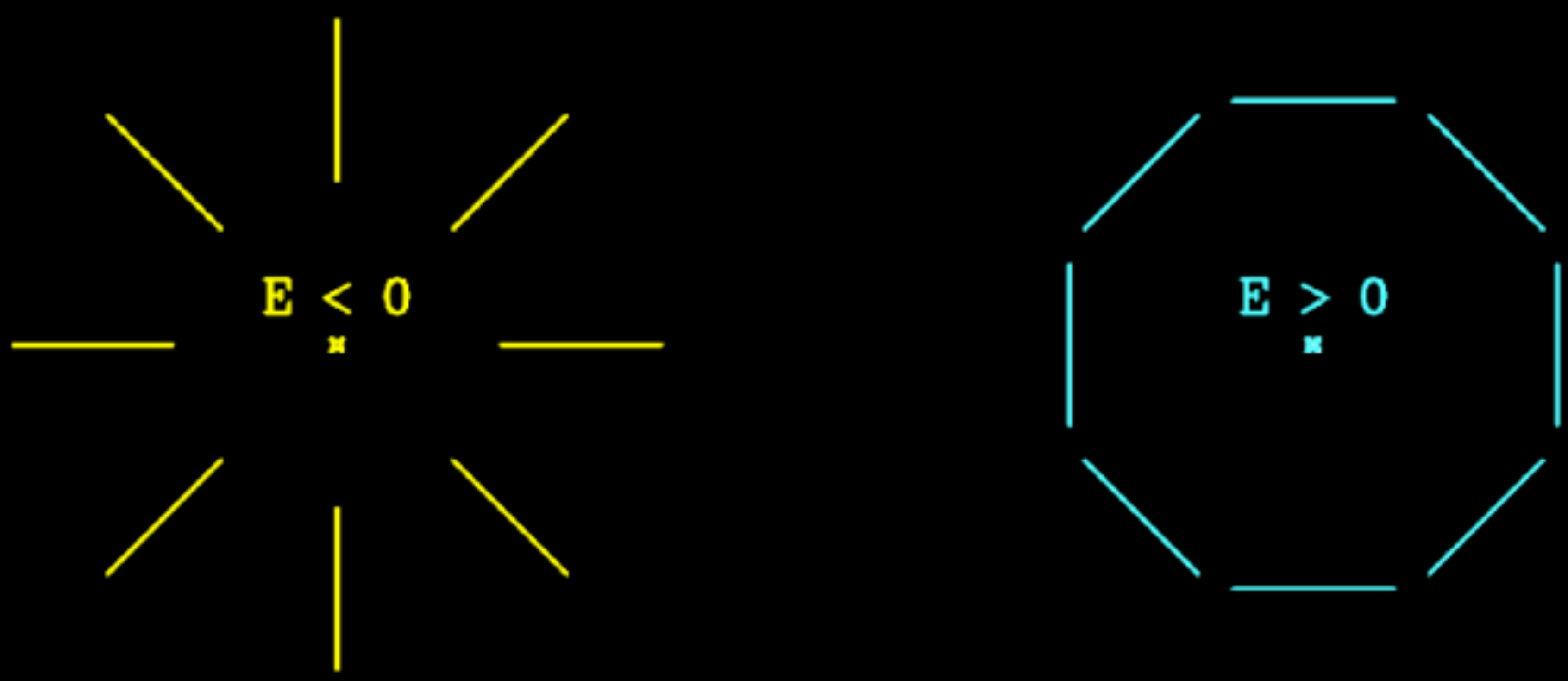
CMB Polarization

This "local quadrupole anisotropy" imparts a net polarization to the scattered light. The polarization direction is *always* either parallel or perpendicular to the direction pointing toward the overdensity.



CMB Polarization

This is a pure "E-mode"
(i.e. a vector pattern with no curl component)

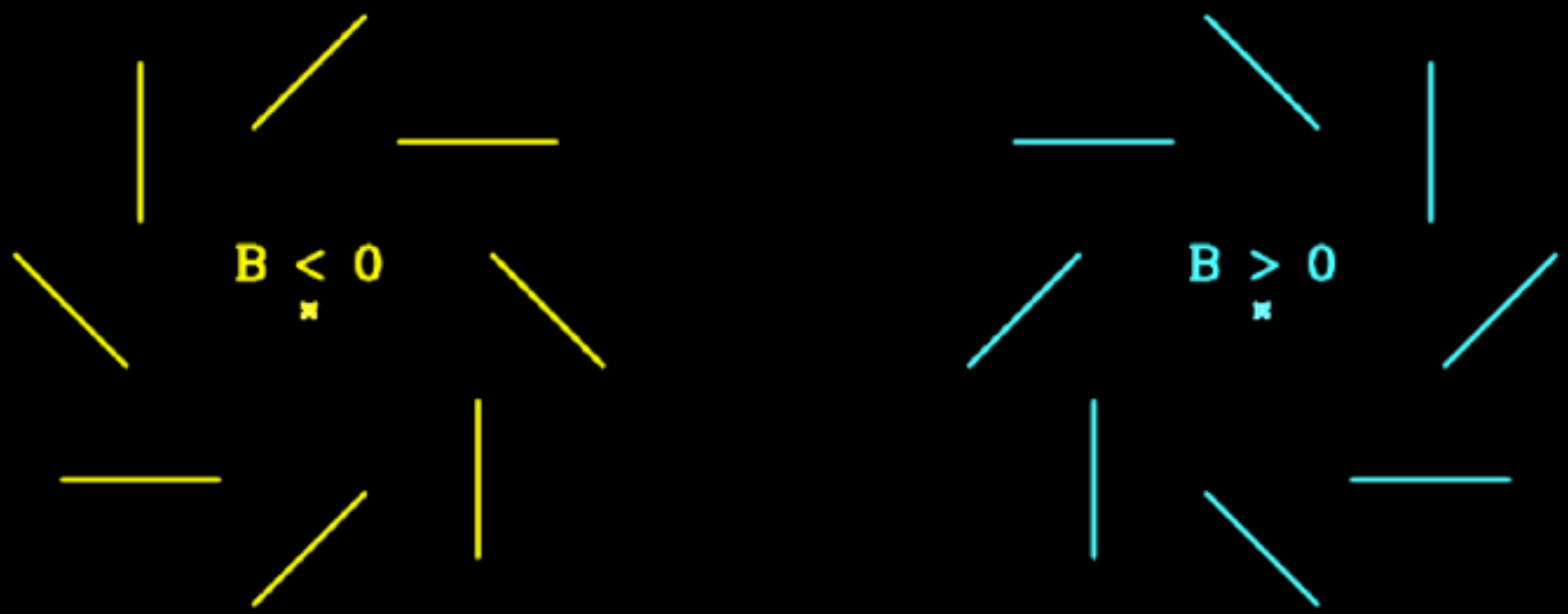


Zaldarriaga, 2003

CMB Polarization

E-modes and B-modes are an orthogonal basis.

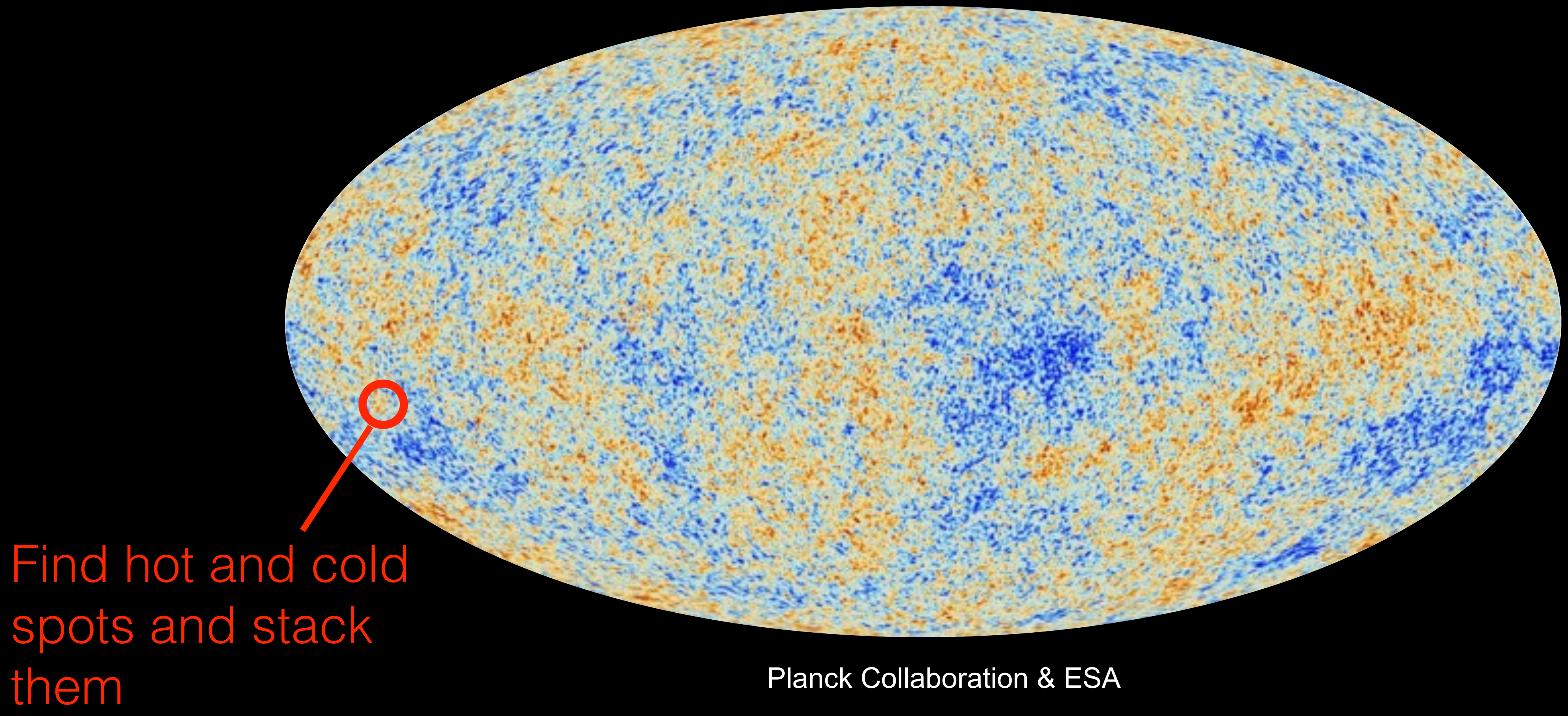
In the standard cosmology, there are *no* B-modes
(i.e. patterns with *only* curl and no divergence)



Zaldarriaga, 2003

CMB Polarization

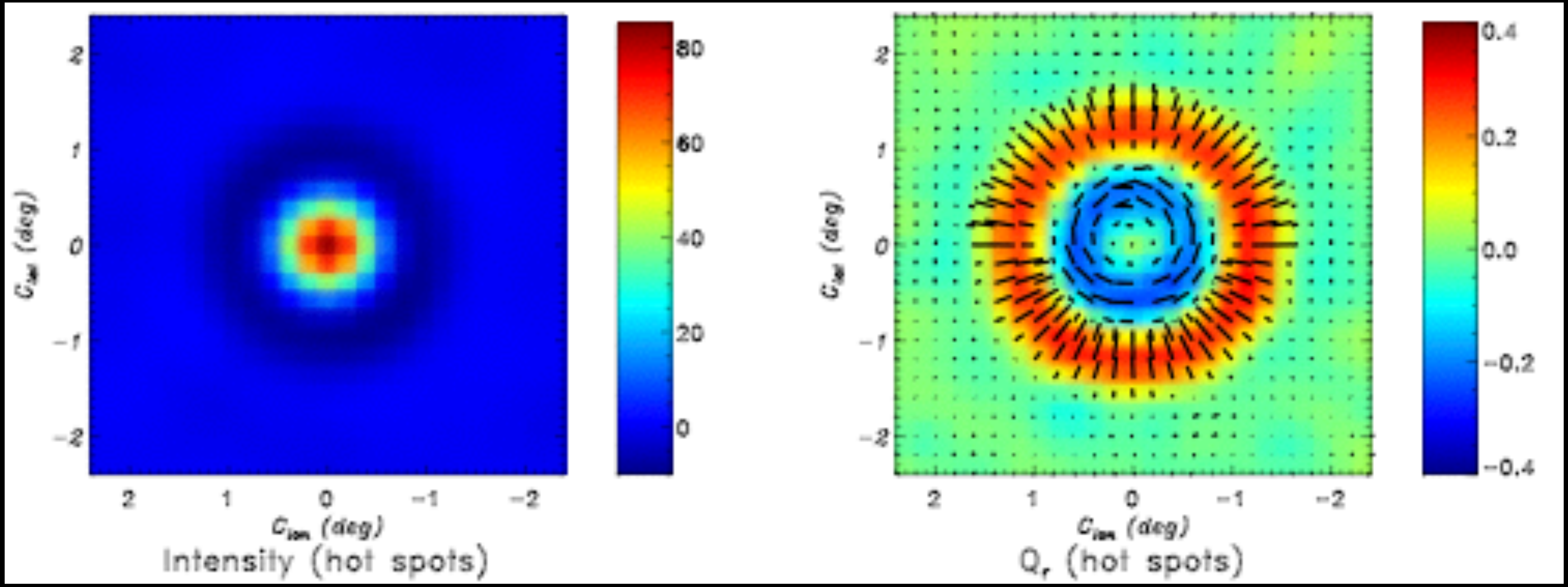
The polarization pattern on the sky is a superposition of these pure E-mode patterns.



Planck Collaboration & ESA

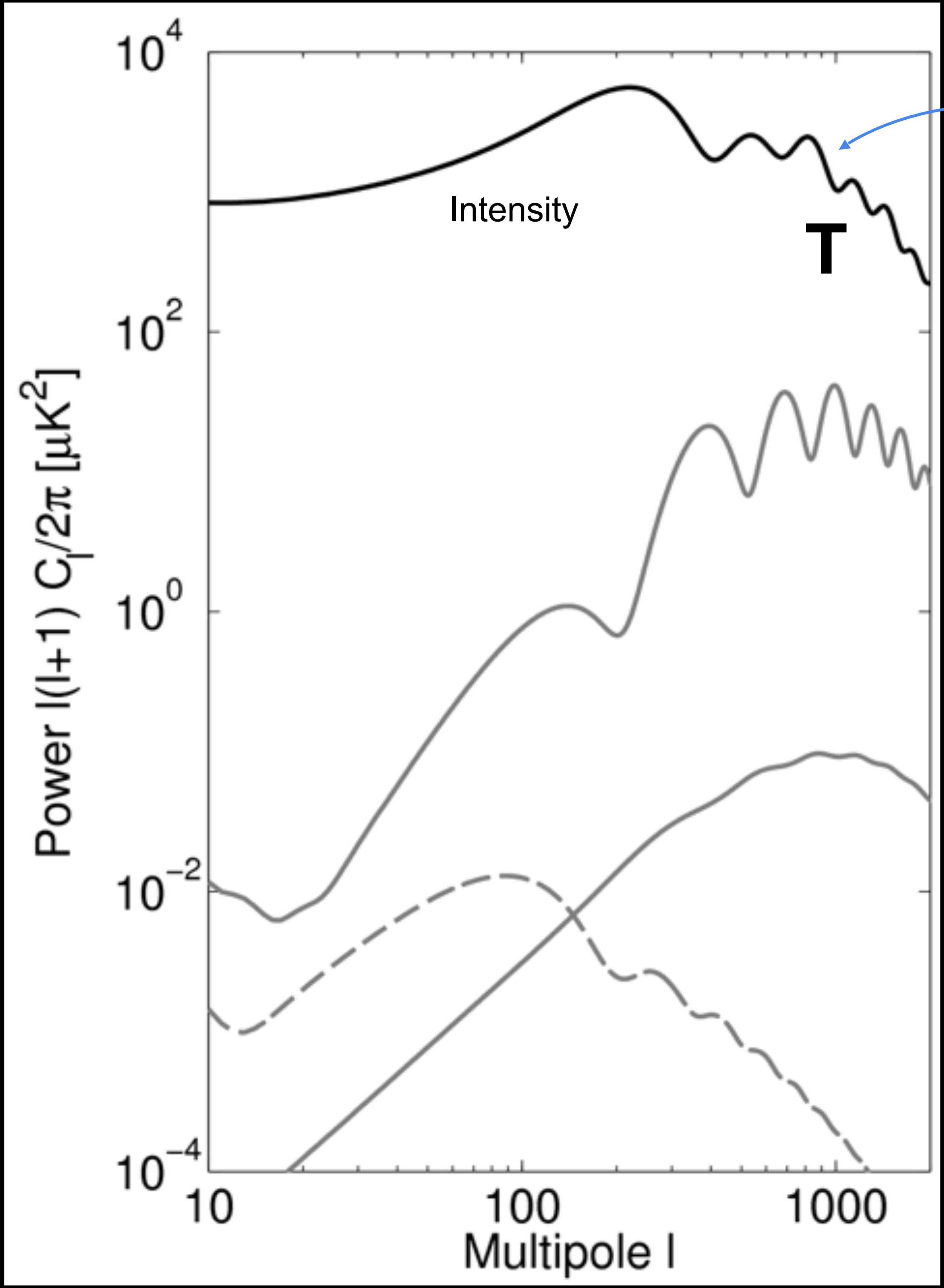
CMB Polarization

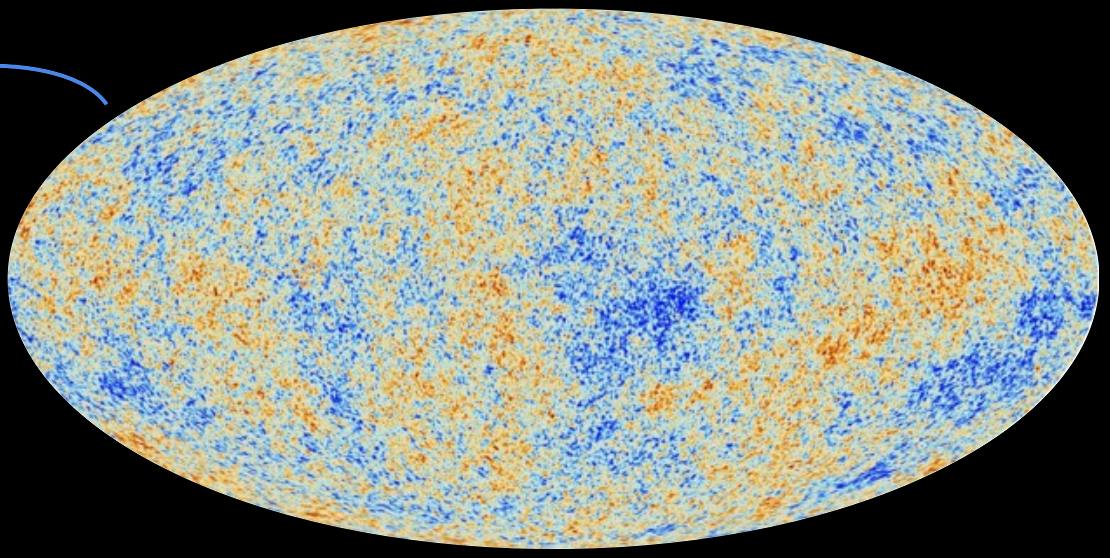
Planck polarization maps stacked over CMB hot spots — pure E-mode



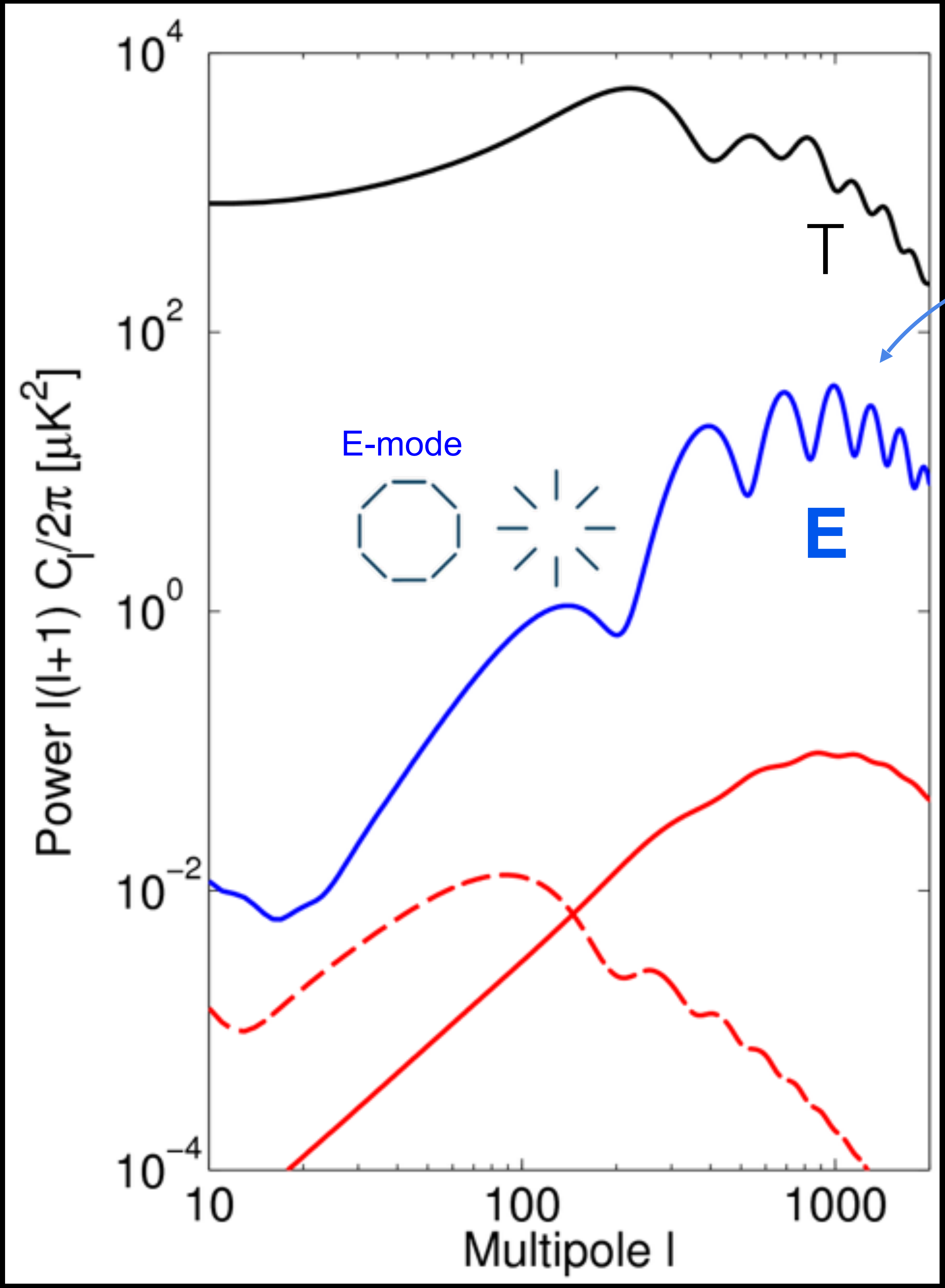
Planck collaboration (2013)

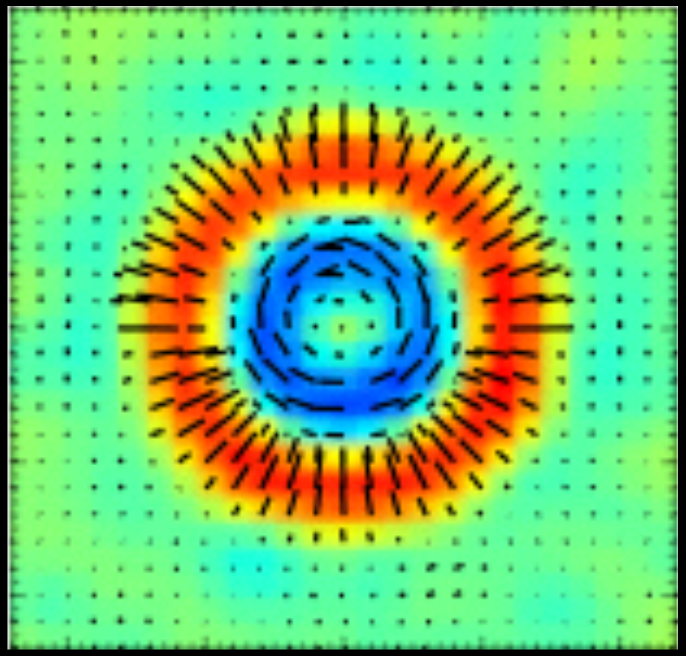
CMB Polarization



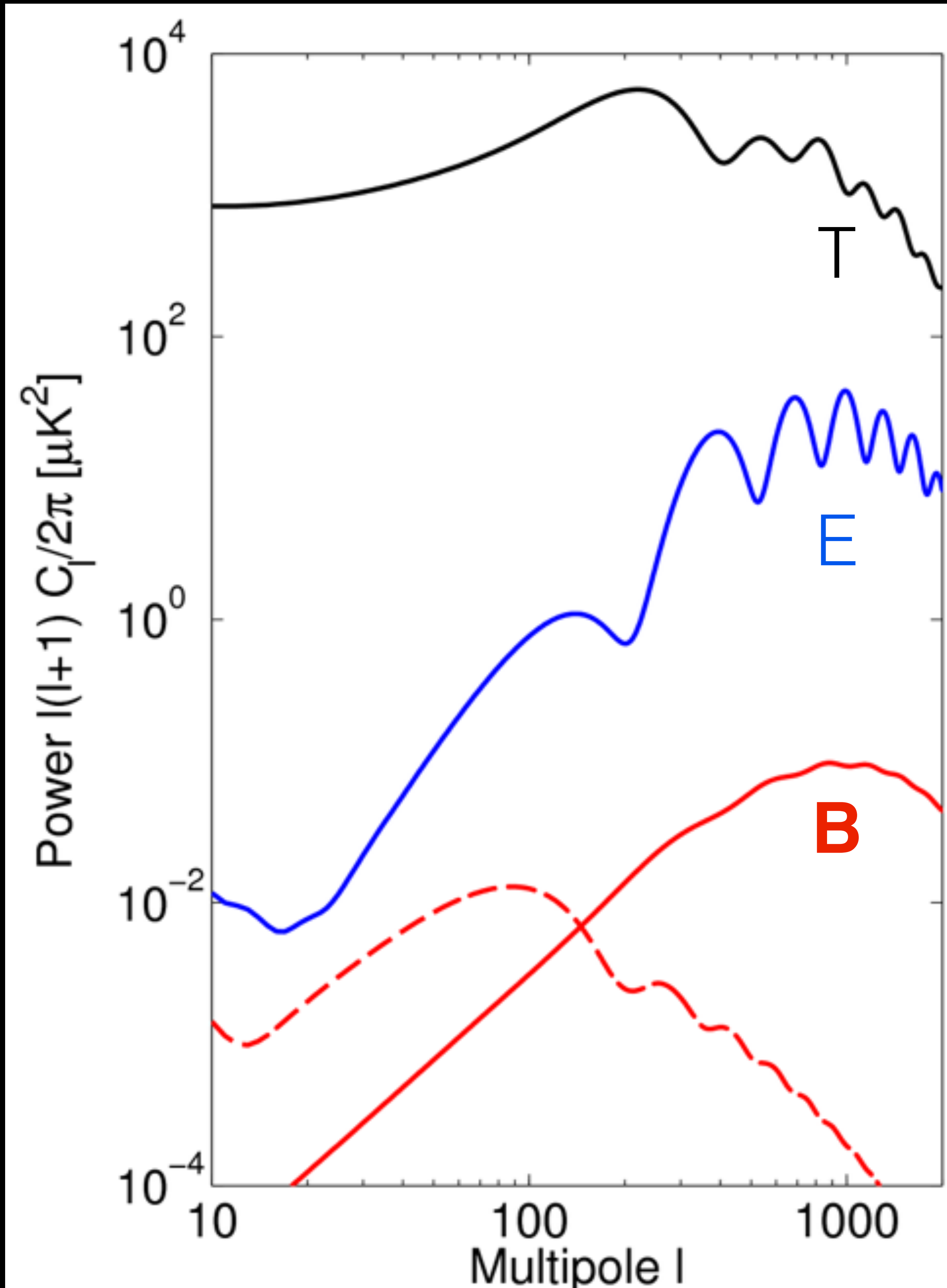


CMB Polarization

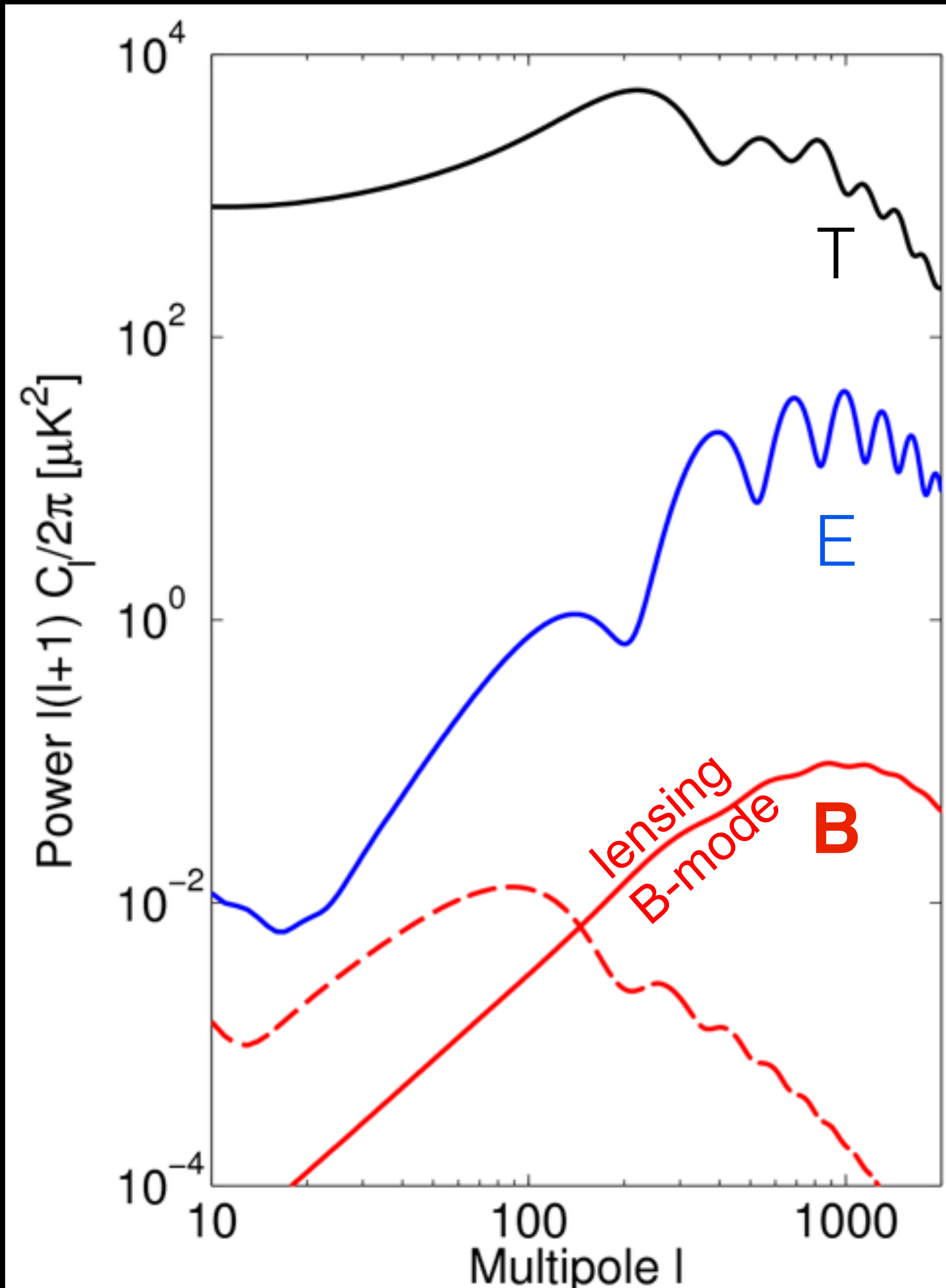




CMB Polarization

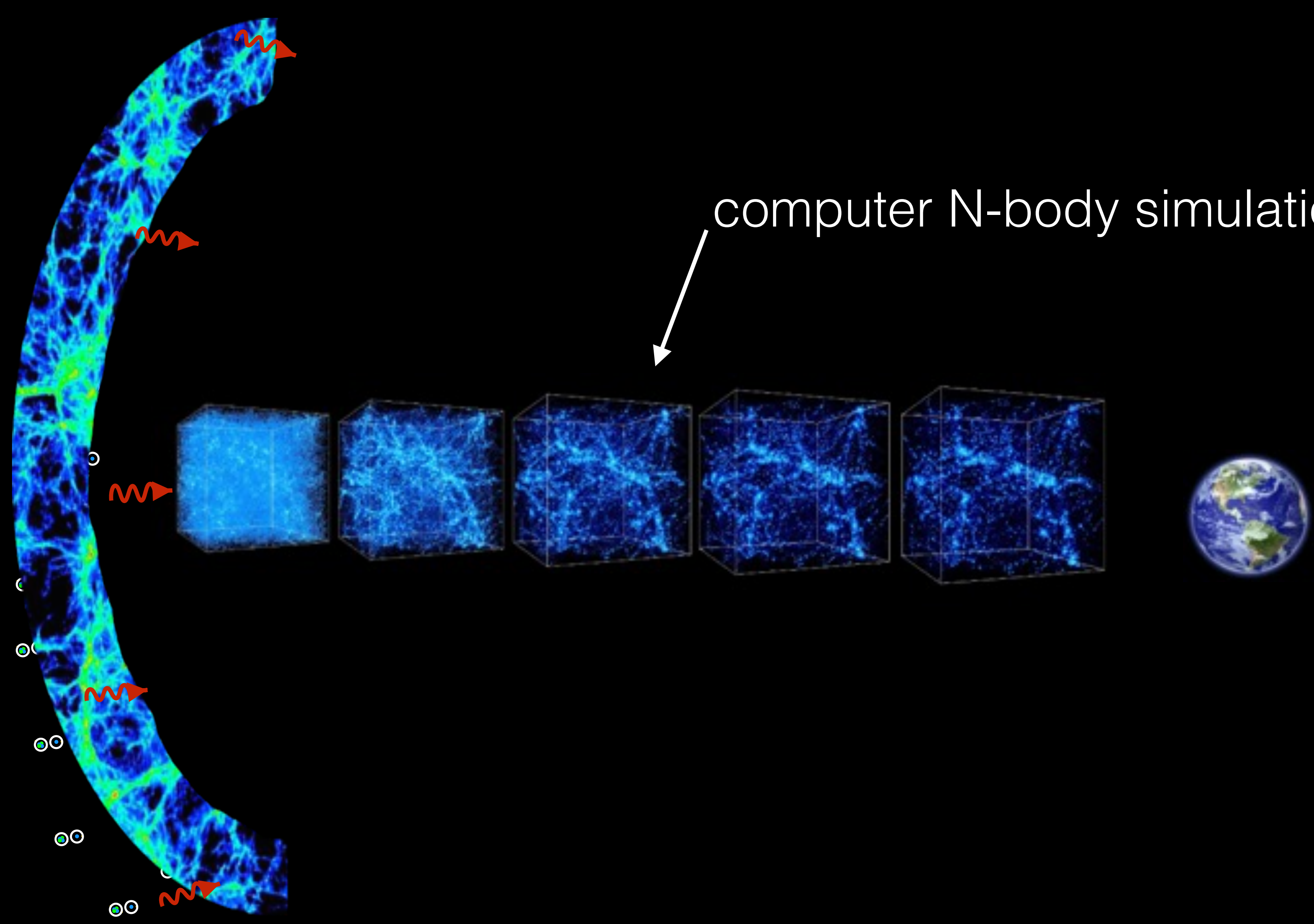


CMB Polarization



Gravitational lensing of CMB

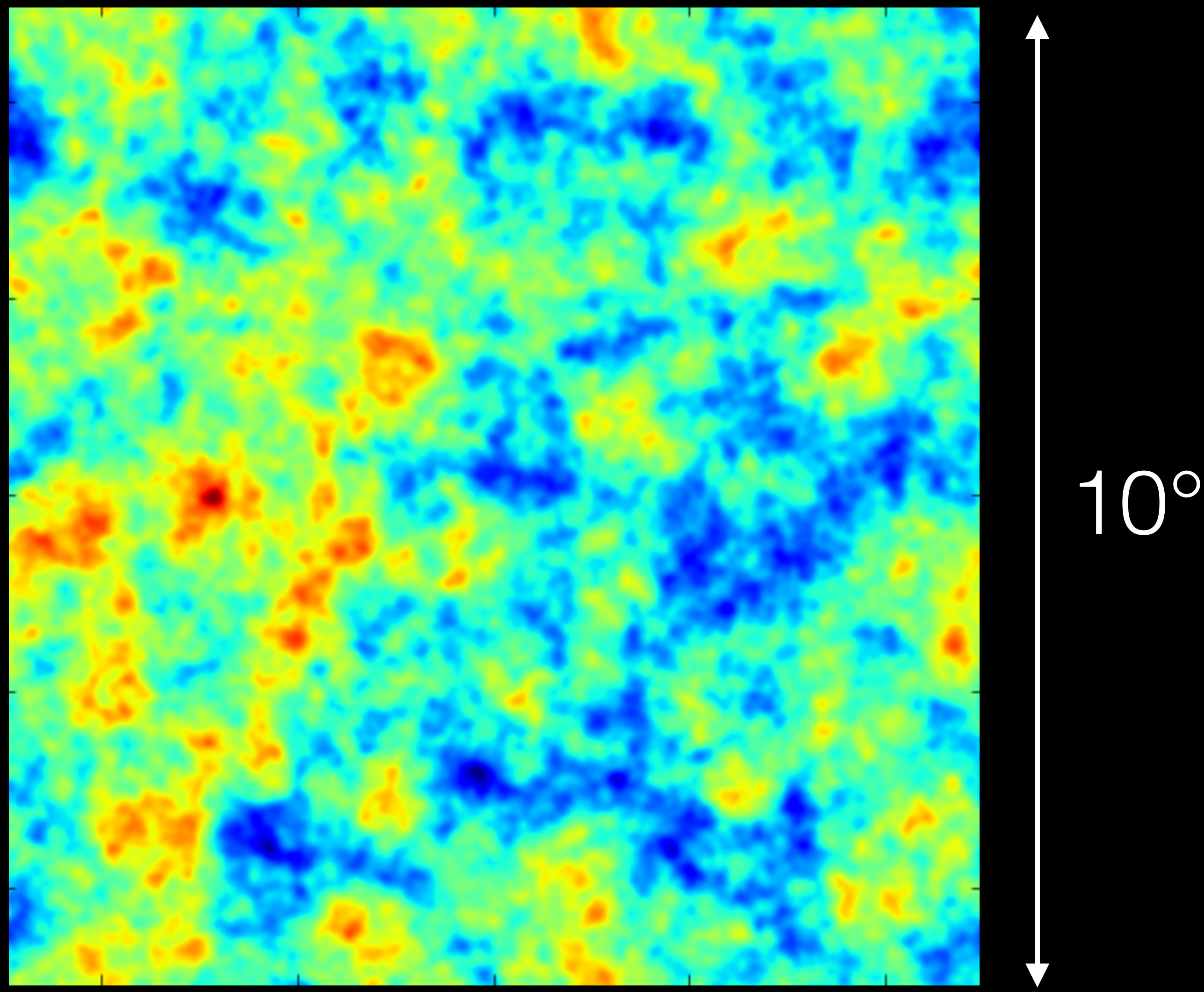
CMB photons moving through the evolving large scale structure
of the universe are gravitationally lensed a little bit



courtesy Center for Cosmological Physics, University of Chicago

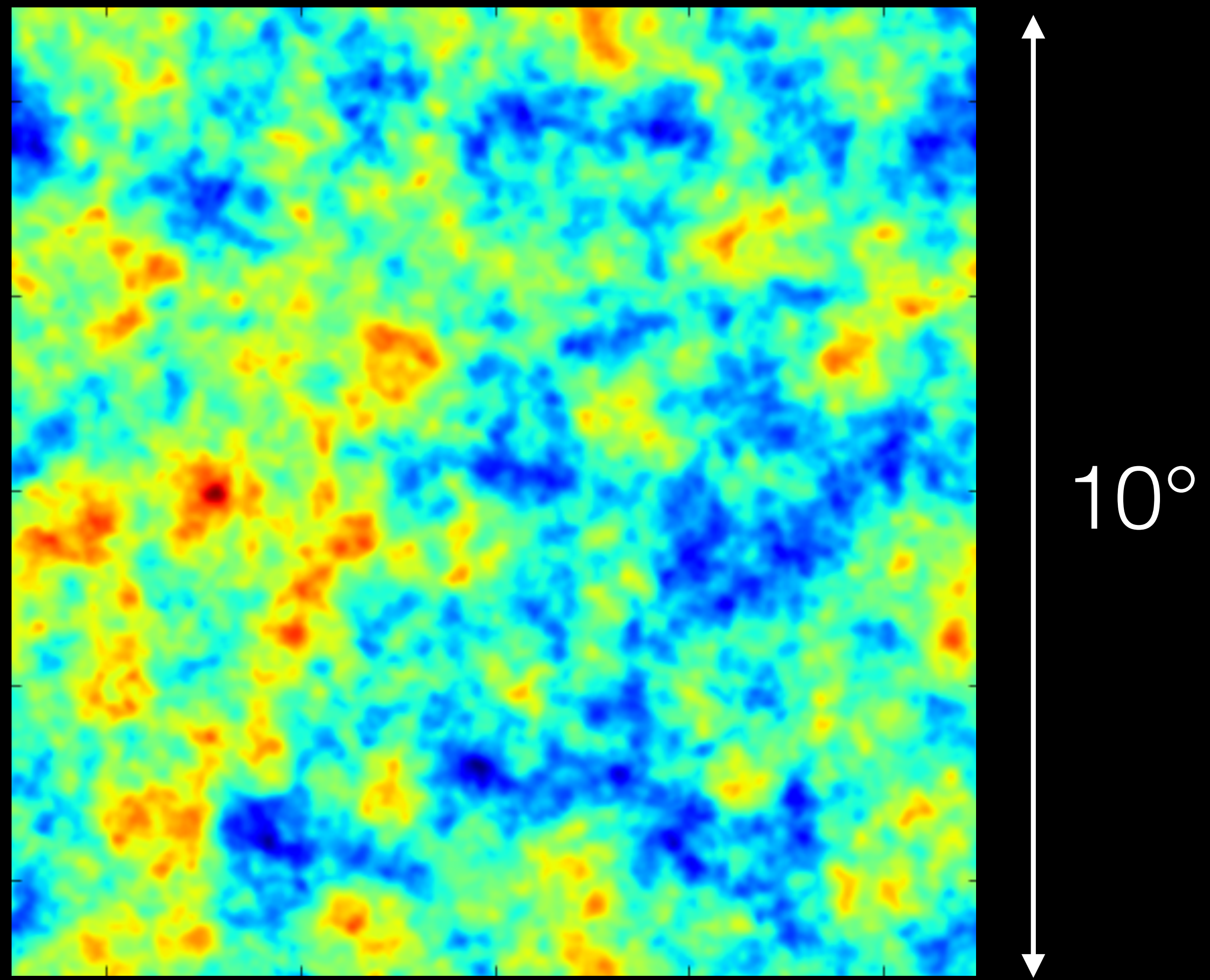
Gravitational lensing of CMB

before gravitational lensing (simulated)

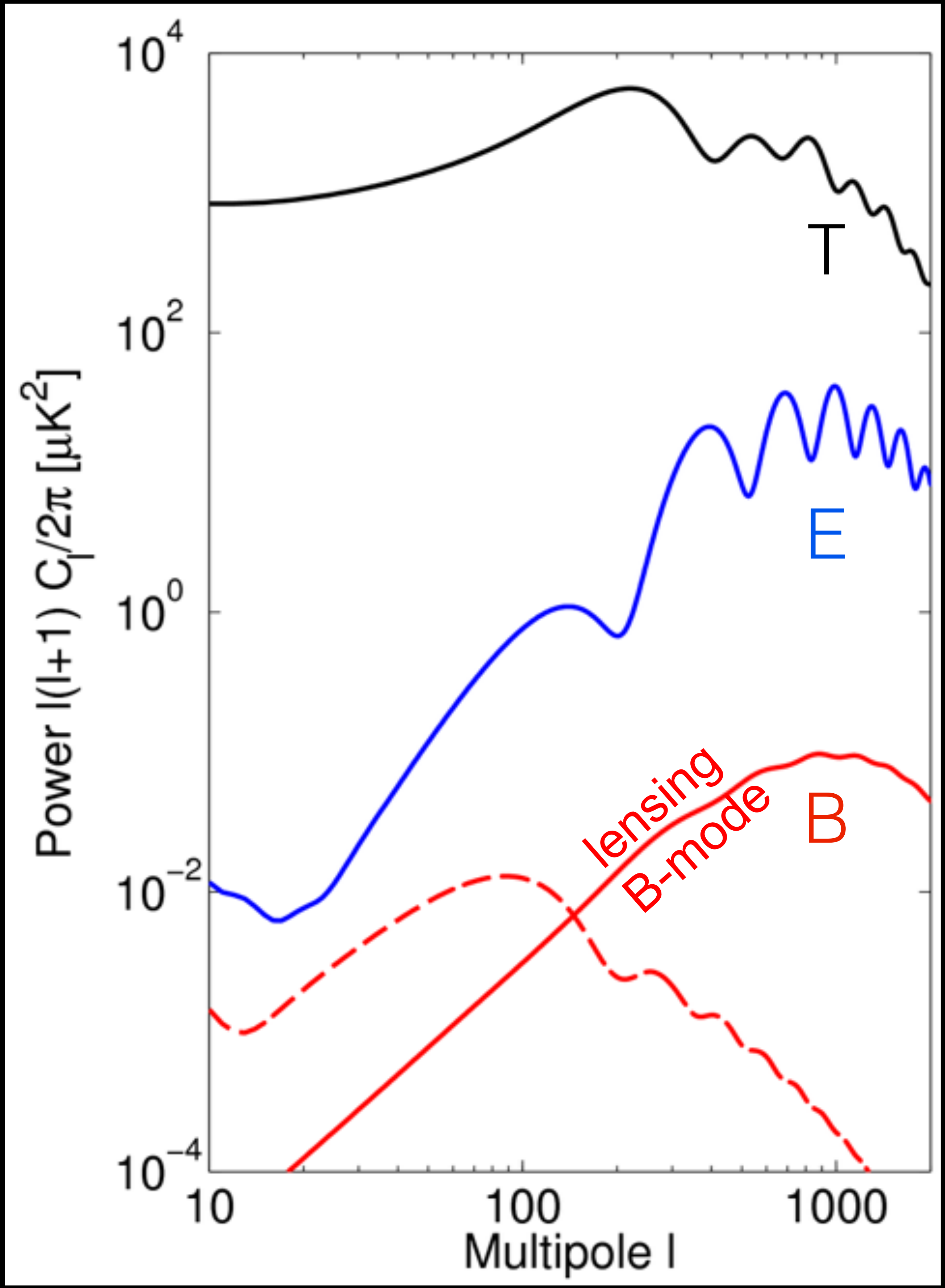


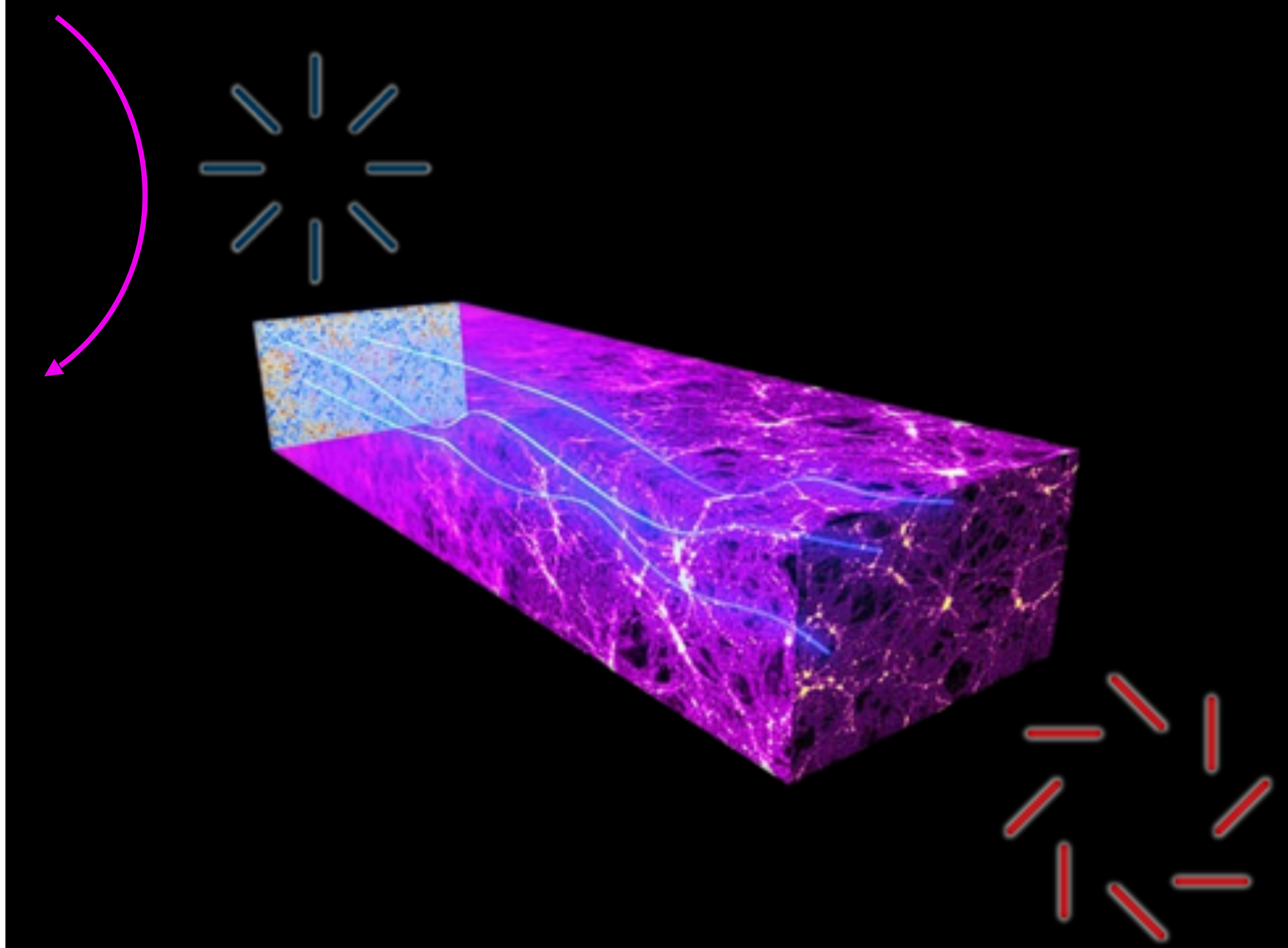
Gravitational lensing of CMB

after gravitational lensing (simulated)

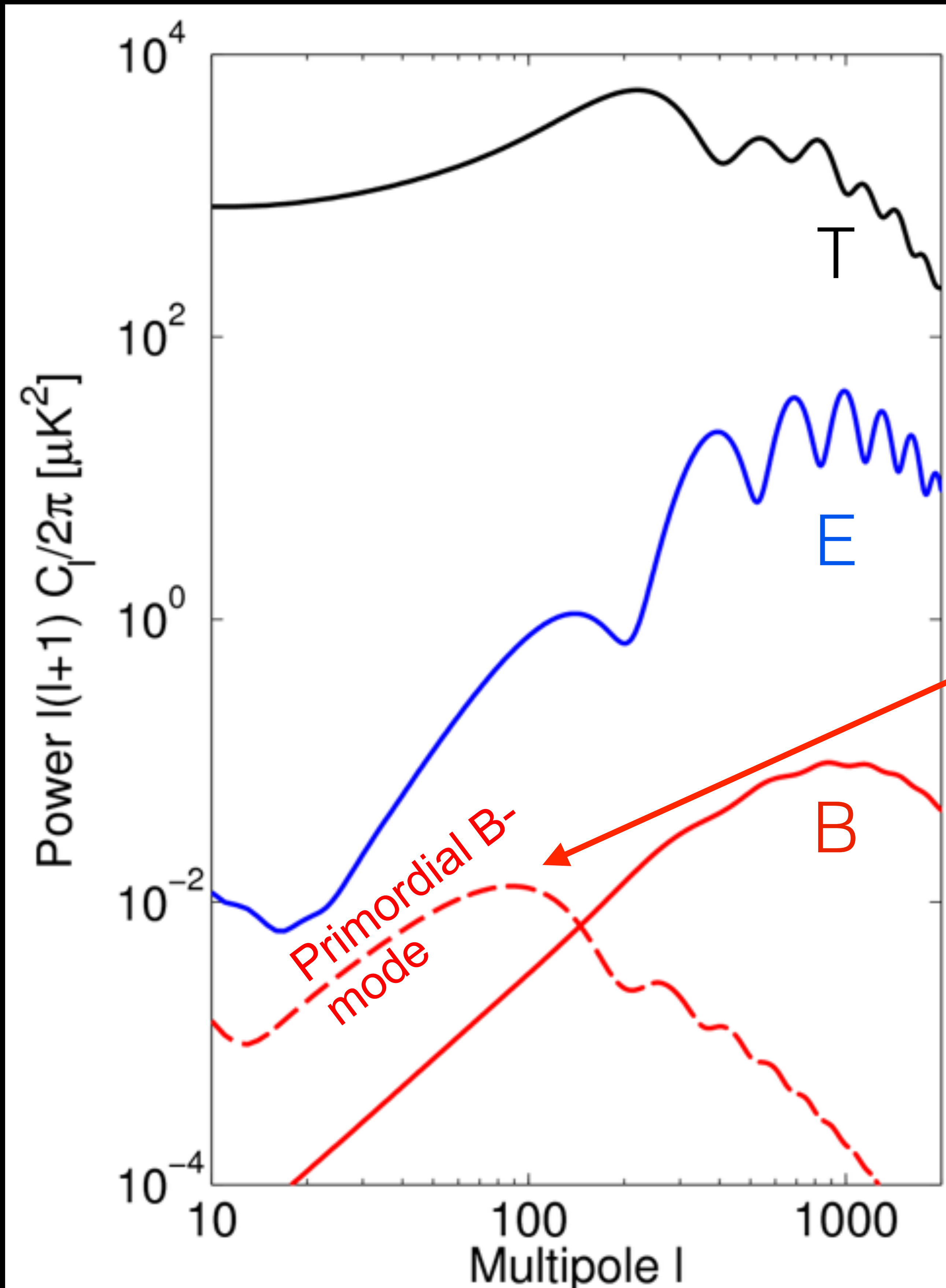


CMB Polarization





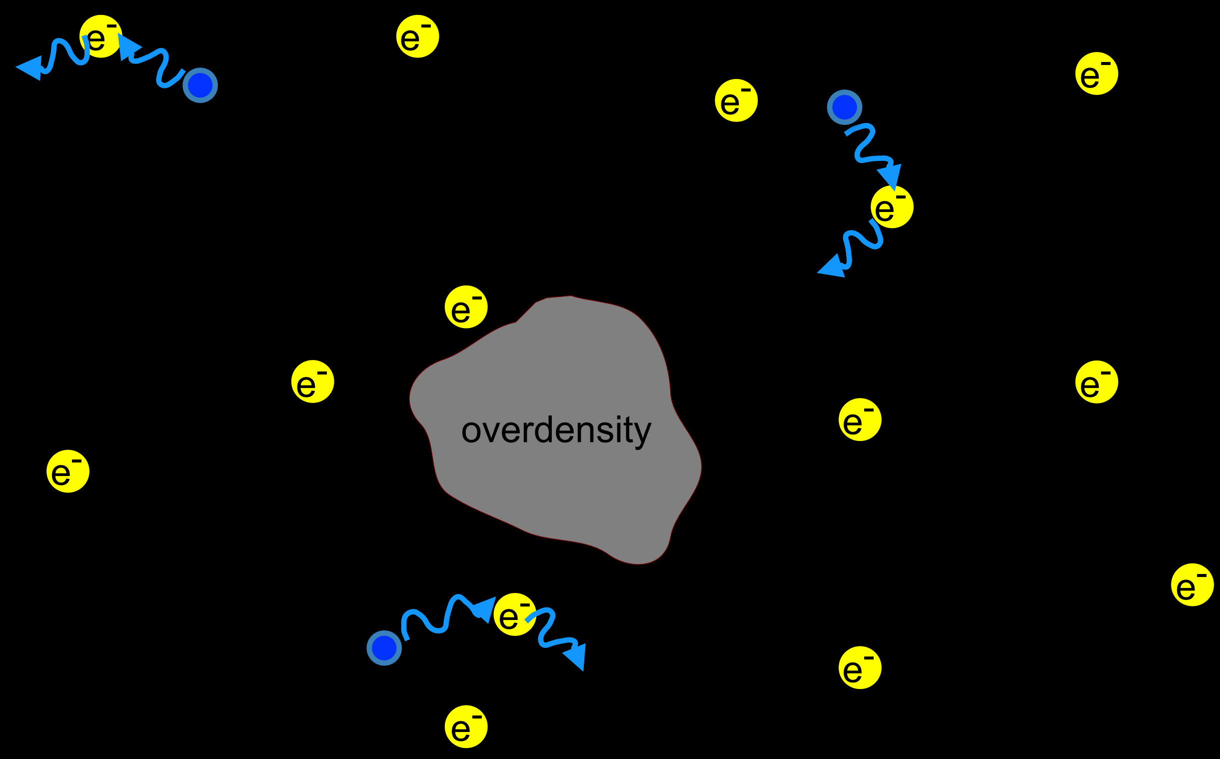
CMB Polarization



B-modes from primordial gravitational waves

CMB Polarization

Gravitational waves present at the time of recombination generically cause polarization.



CMB Polarization

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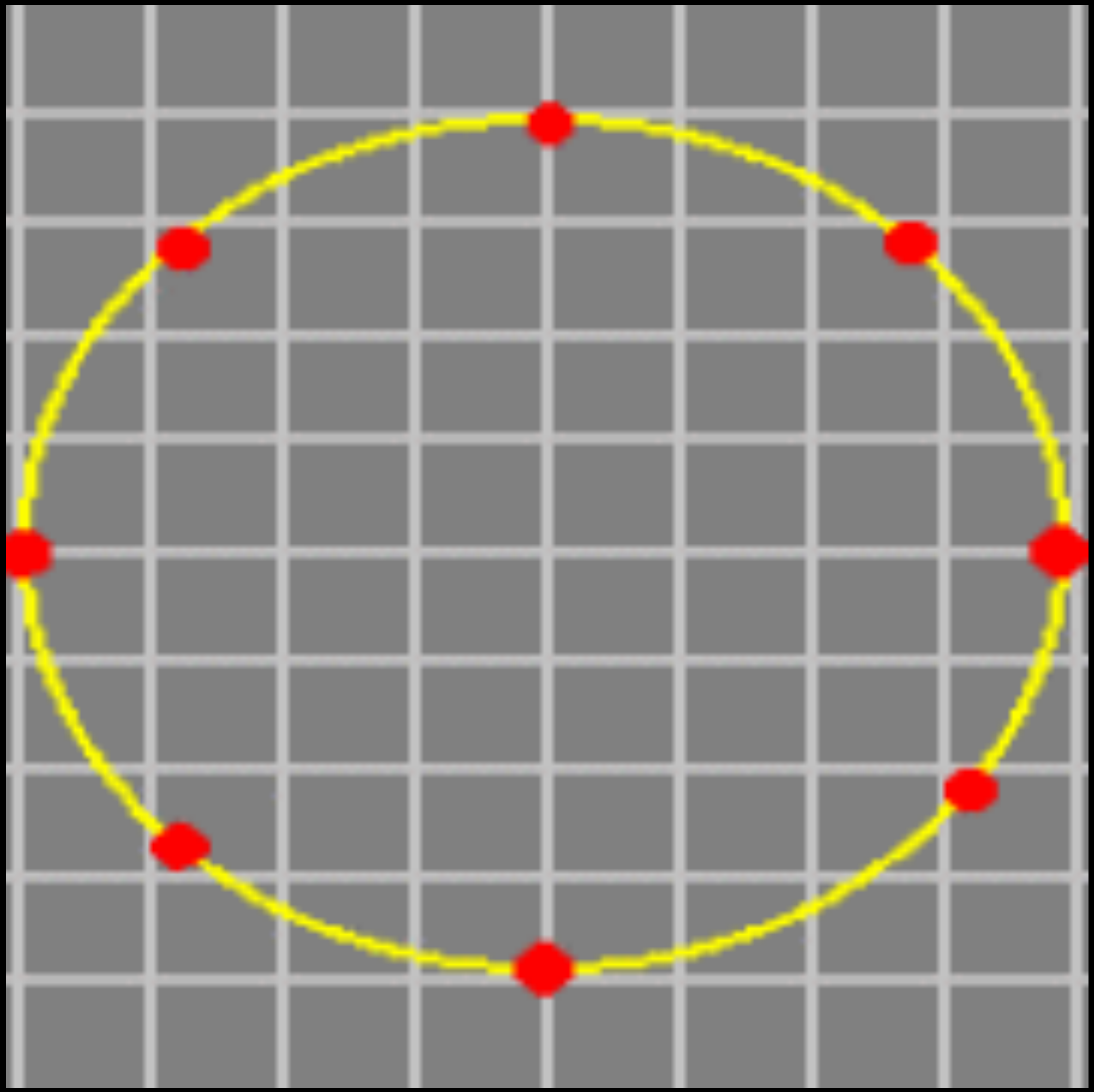

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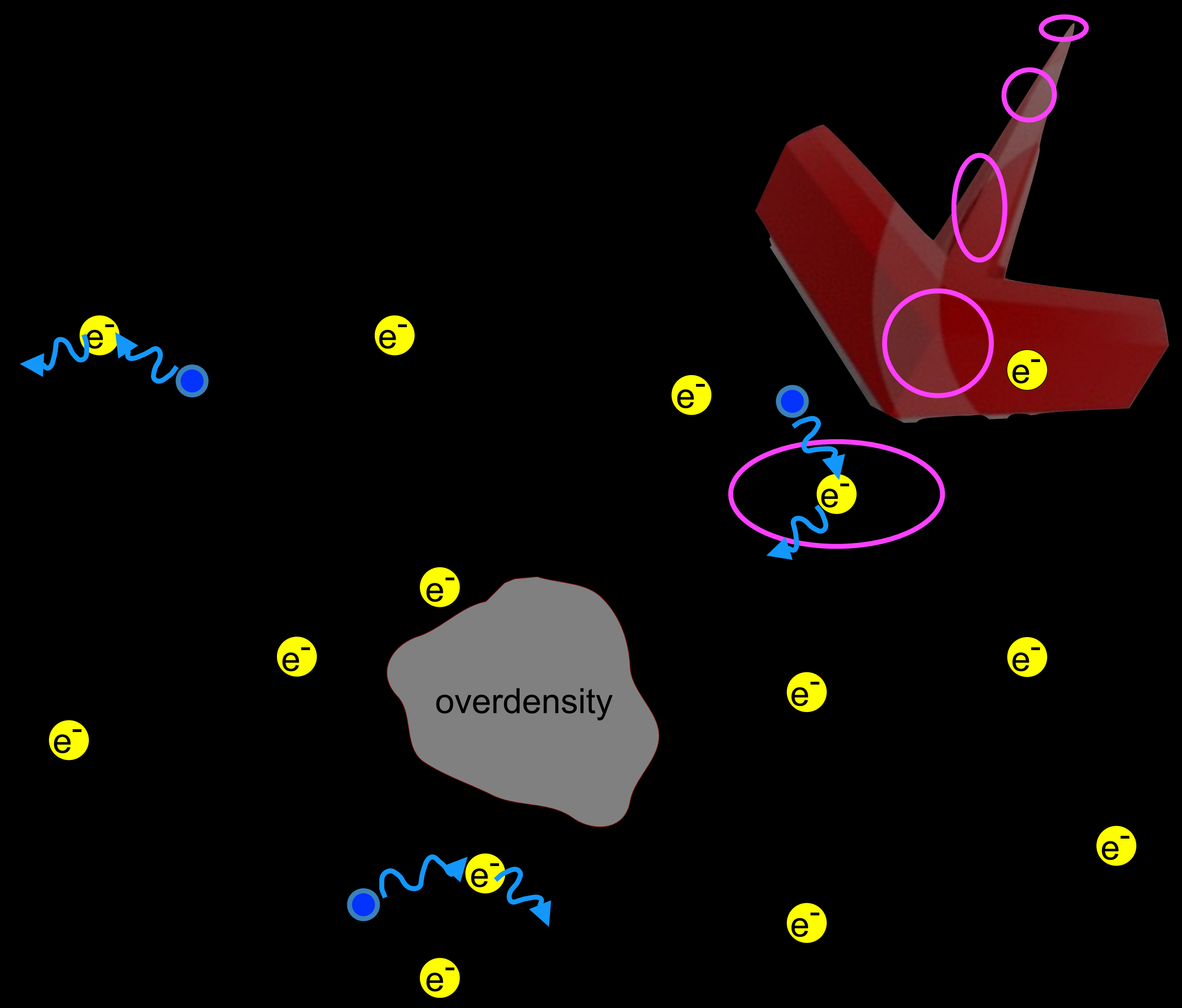
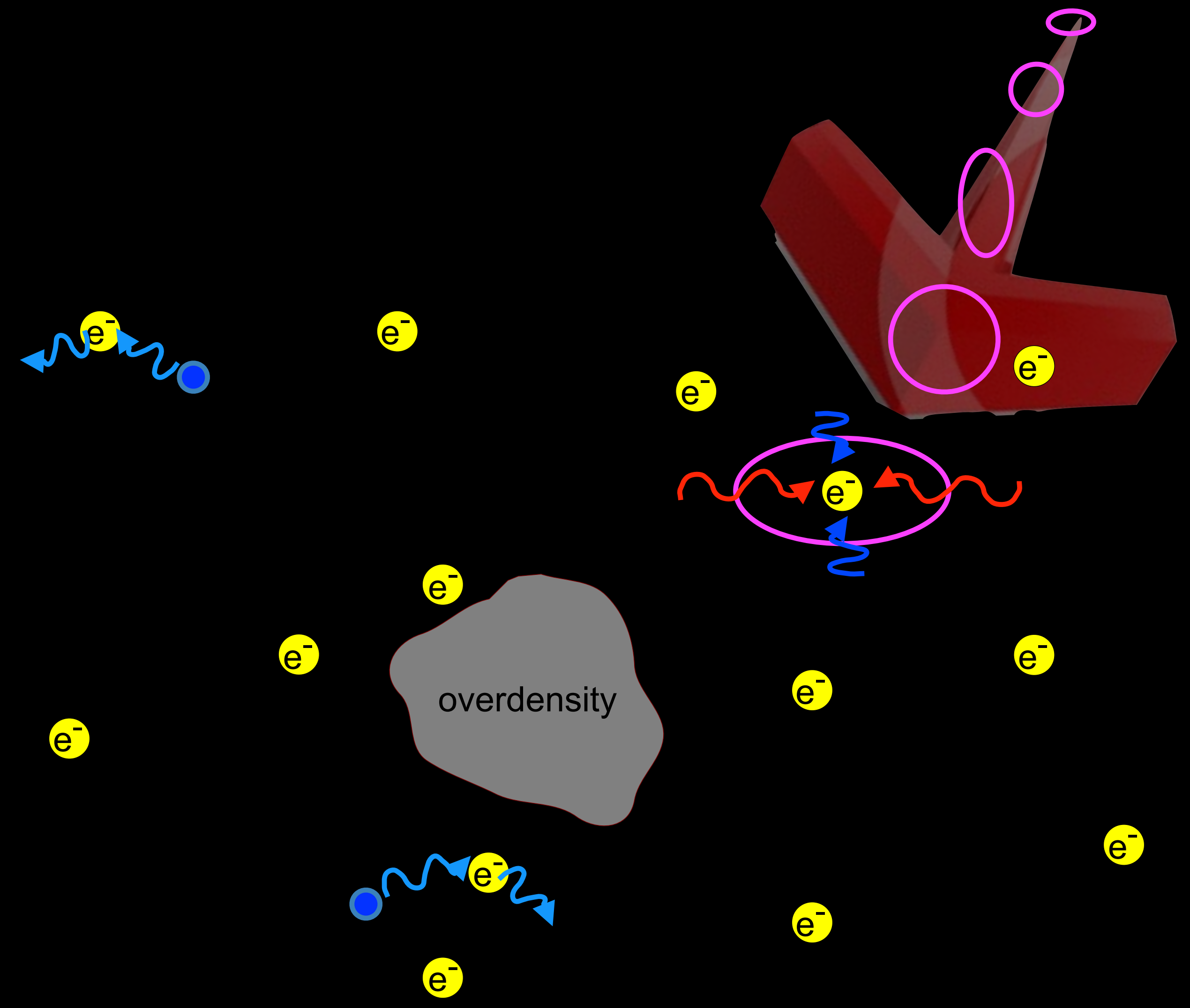


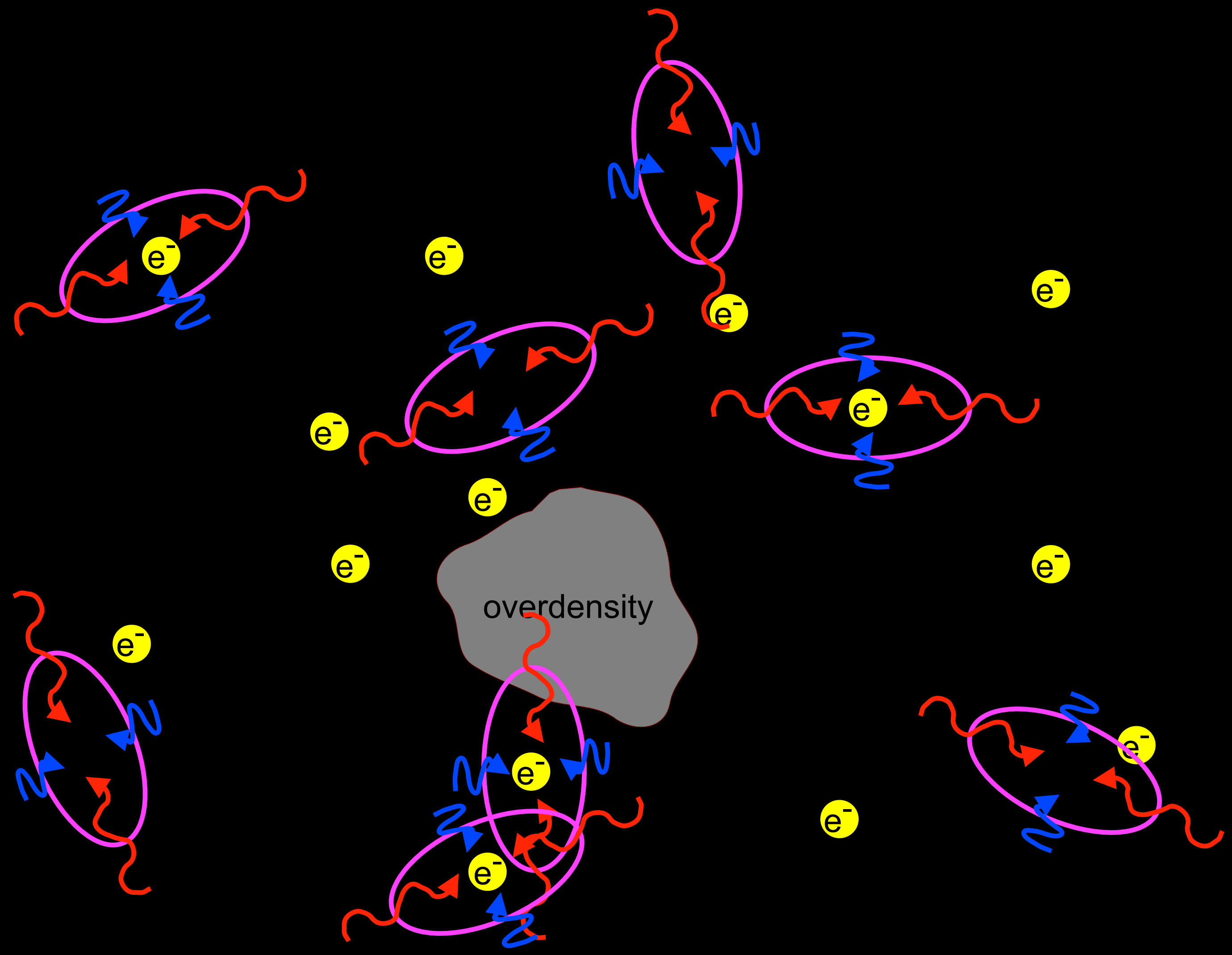
CMB Polarization

Gravitational waves present at the time of recombination generically cause polarization.



CMB Polarization

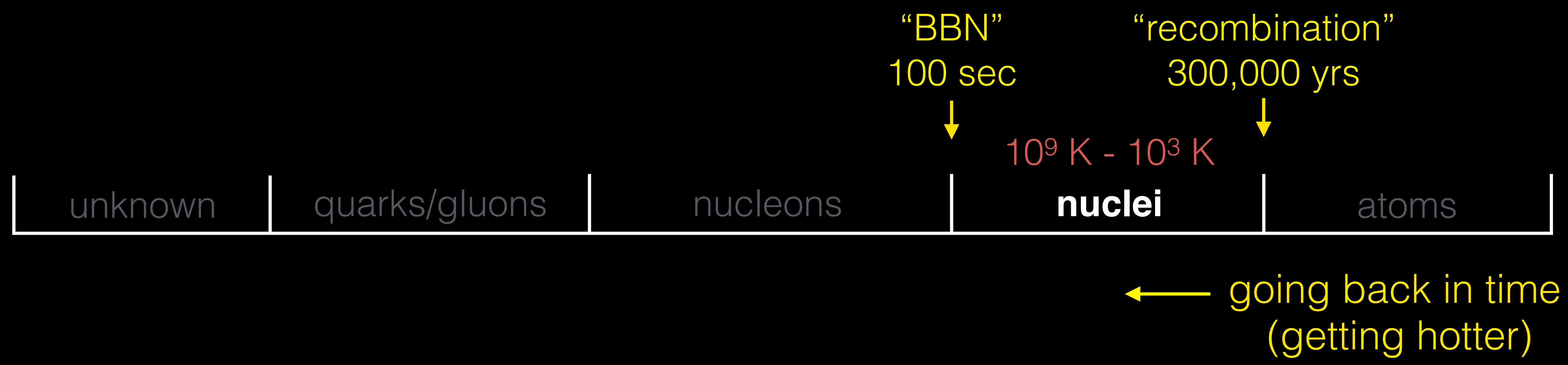
Their random orientations produce E-modes and B-modes nearly *indiscriminately*.



CMB Polarization

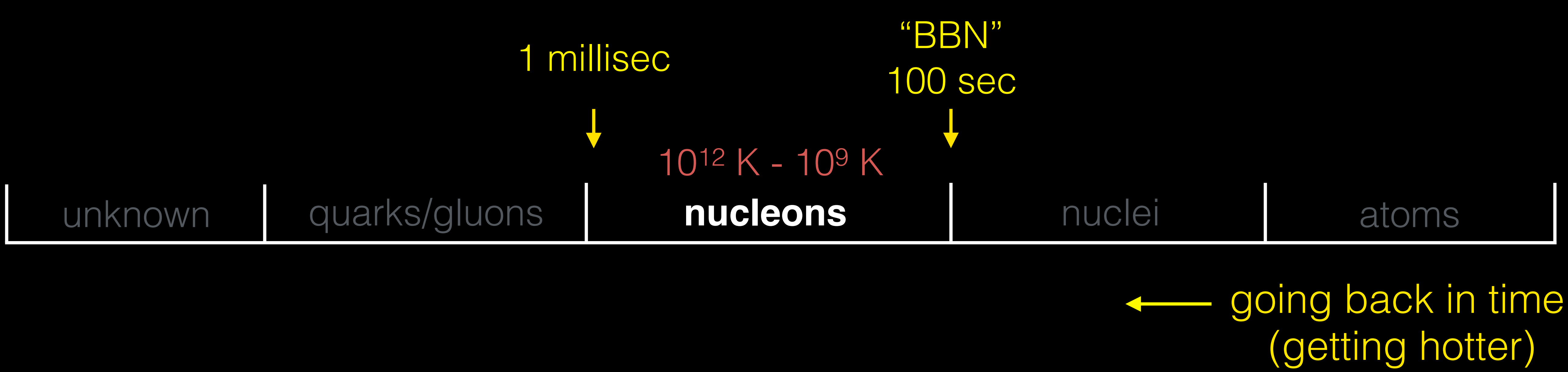
Whence the gravitational waves?

Thermal history of the Universe



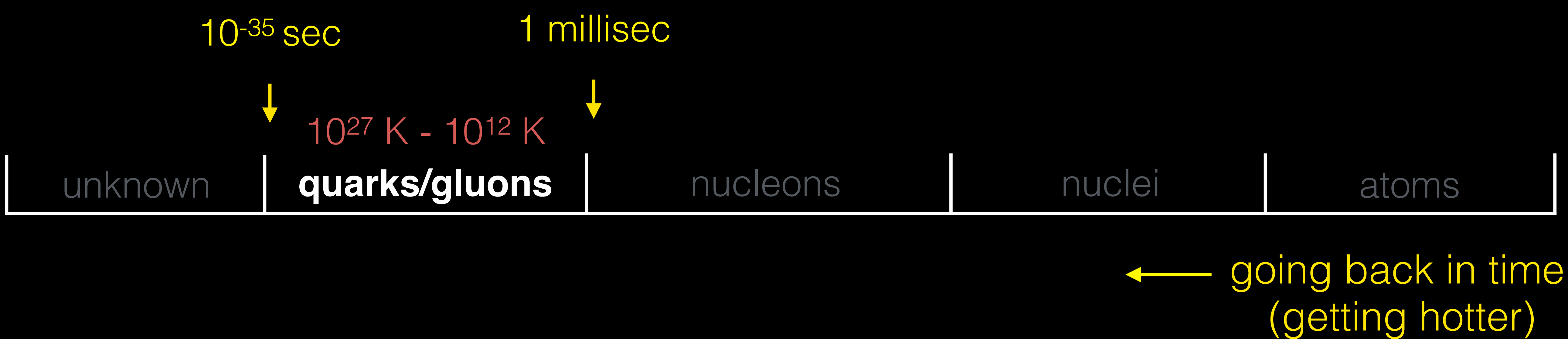
Thermal history of the Universe

Evidence: light element abundances (H, He, Li) match predictions of Big Bang Nucleosynthesis

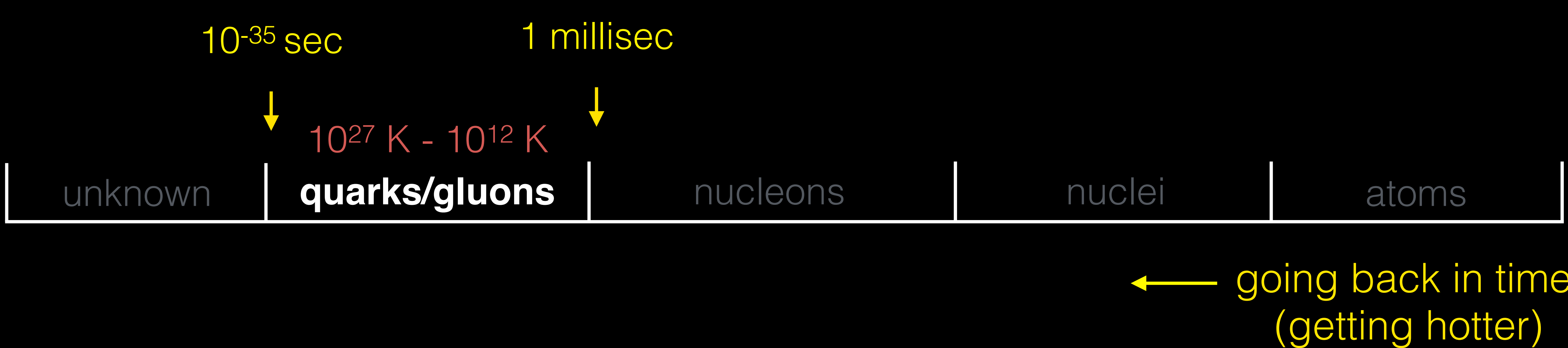


Thermal history of the Universe

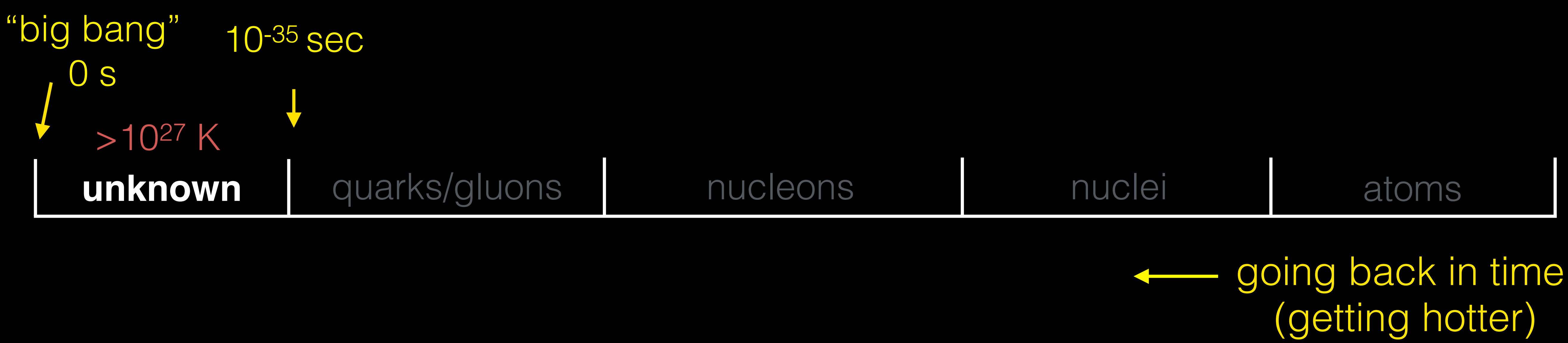
No direct evidence from observational cosmology, but physics is testable at collider energies



Thermal history of the Universe



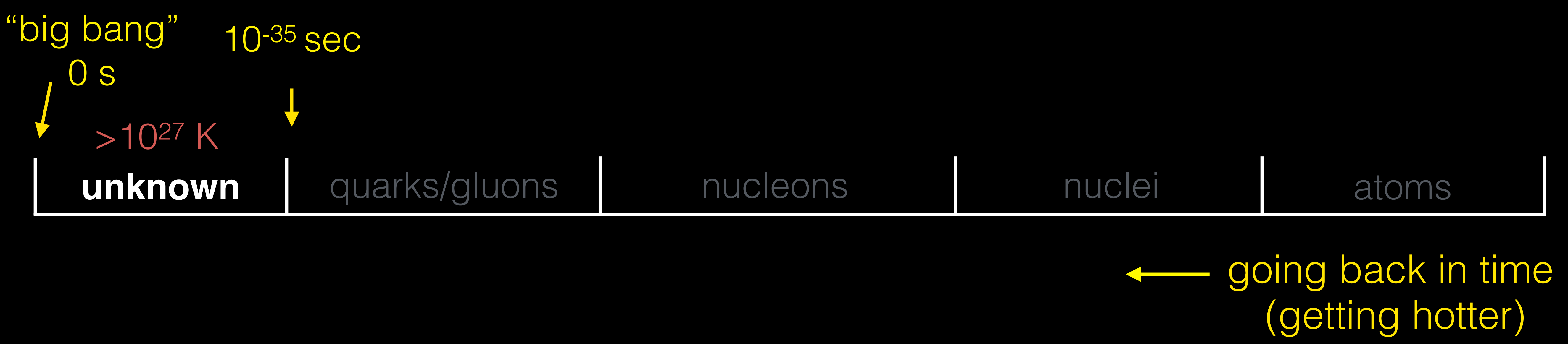
Thermal history of the Universe



Thermal history of the Universe

Inflation?

Exponential expansion turns quantum fluctuations into macroscopic density inhomogeneities.



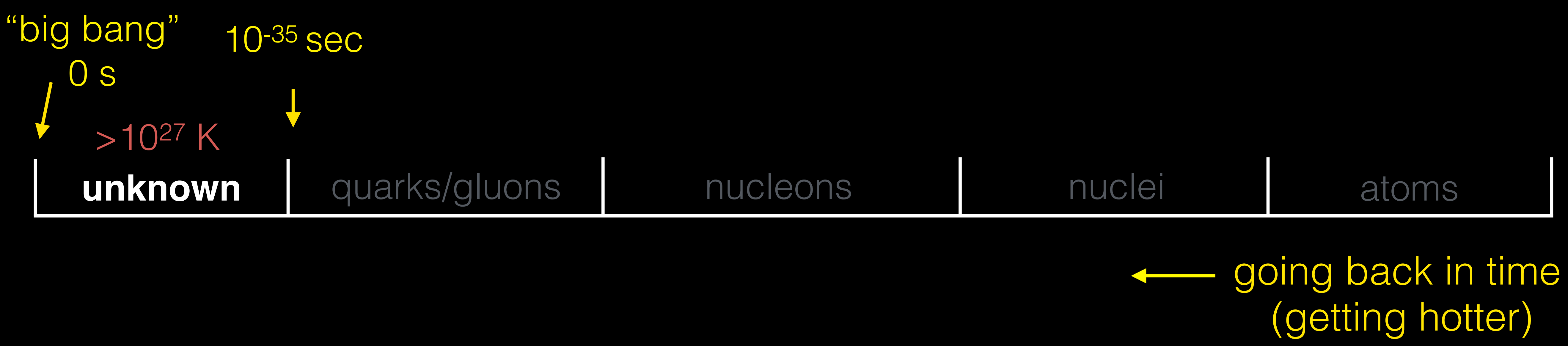
Thermal history of the Universe

Inflation?

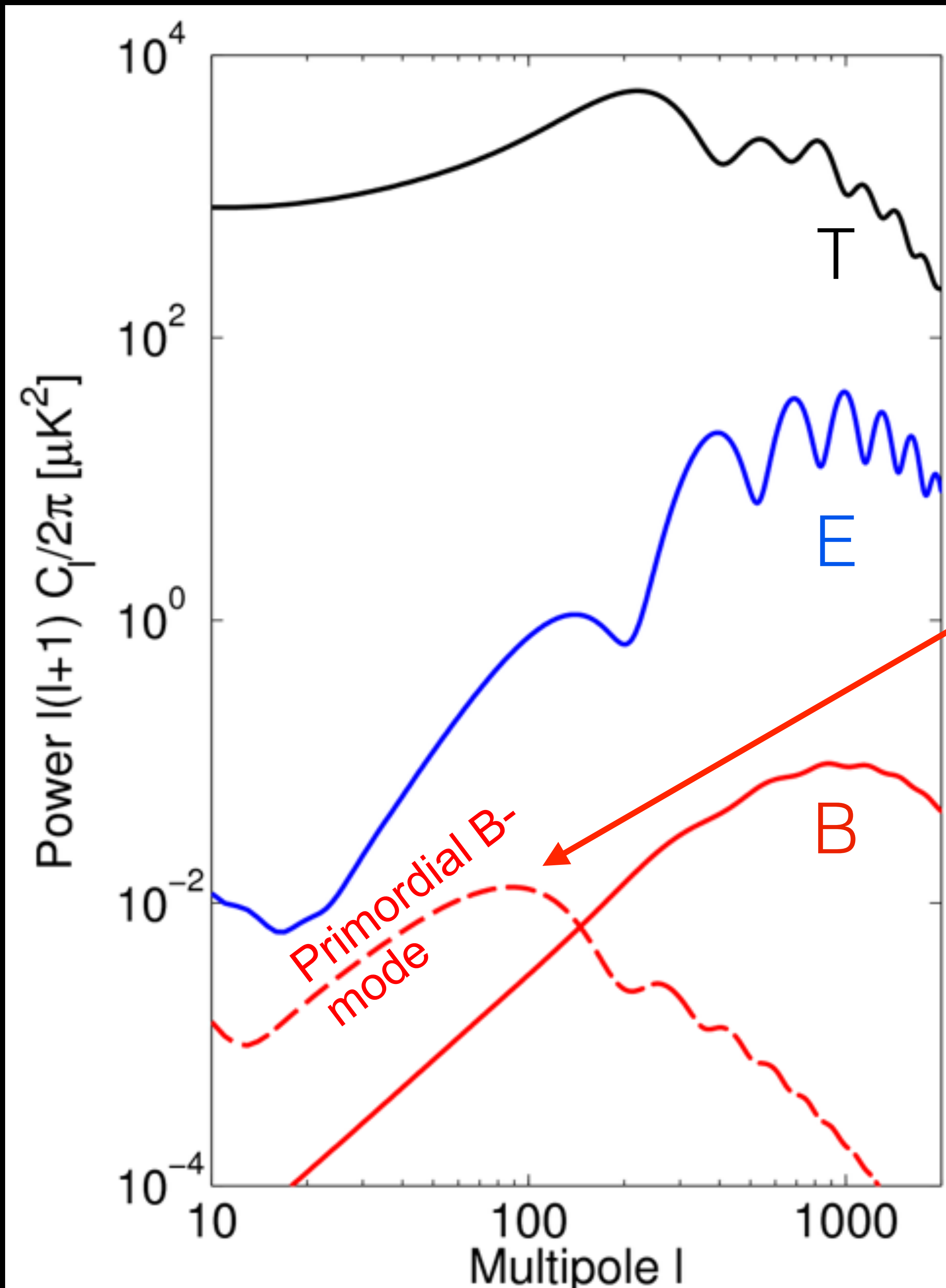
density inhomogeneities ↔ scalar metric perturbations
gravitational waves ↔ tensor metric perturbations

Inflation produces both!

The ratio of the amplitude of tensor perturbations to scalar perturbations is parametrized by r=T/S



CMB Polarization

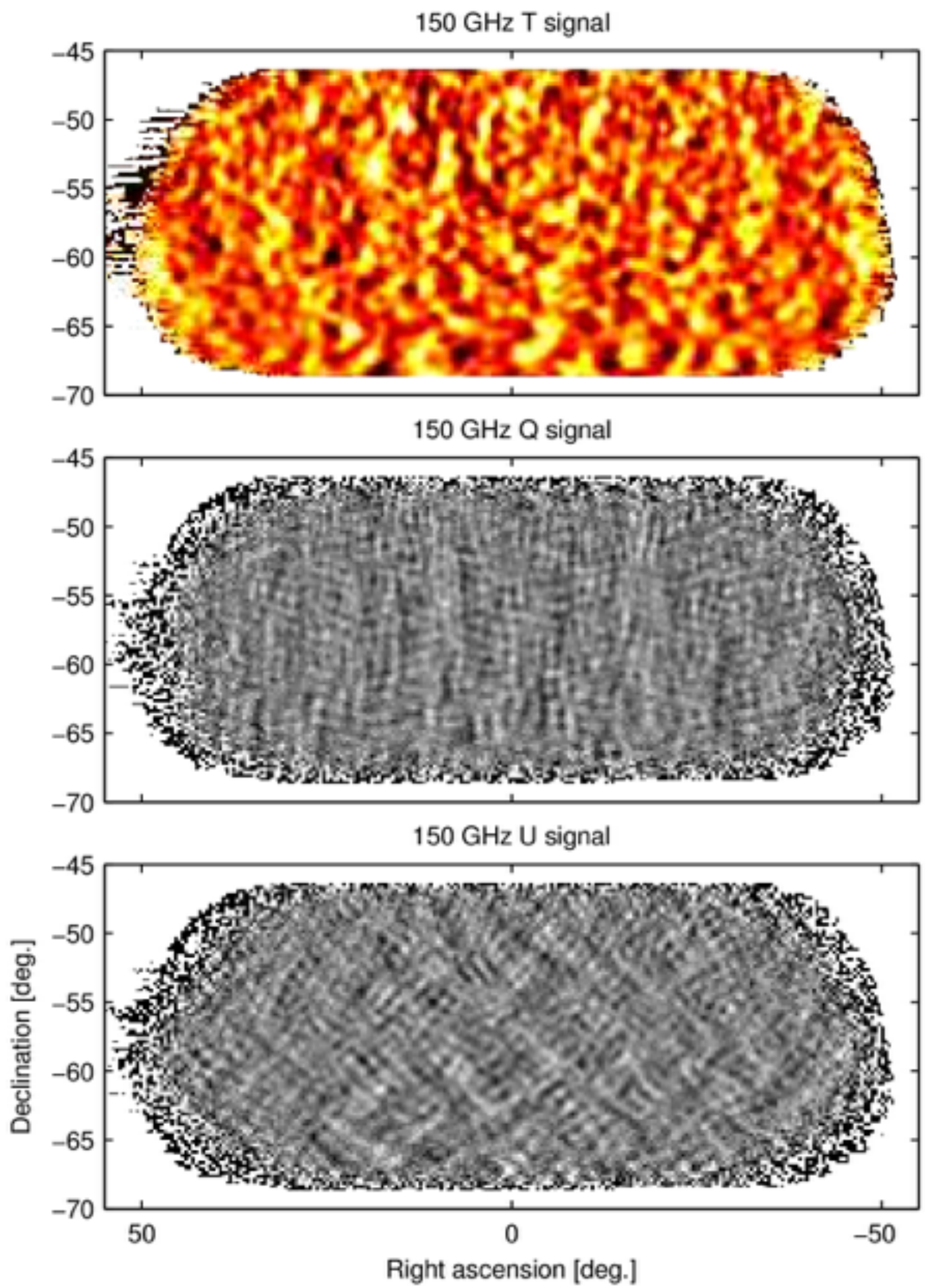


Inflationary gravitational waves are unique source of B-modes

→ peaking at l≈100: degree scales

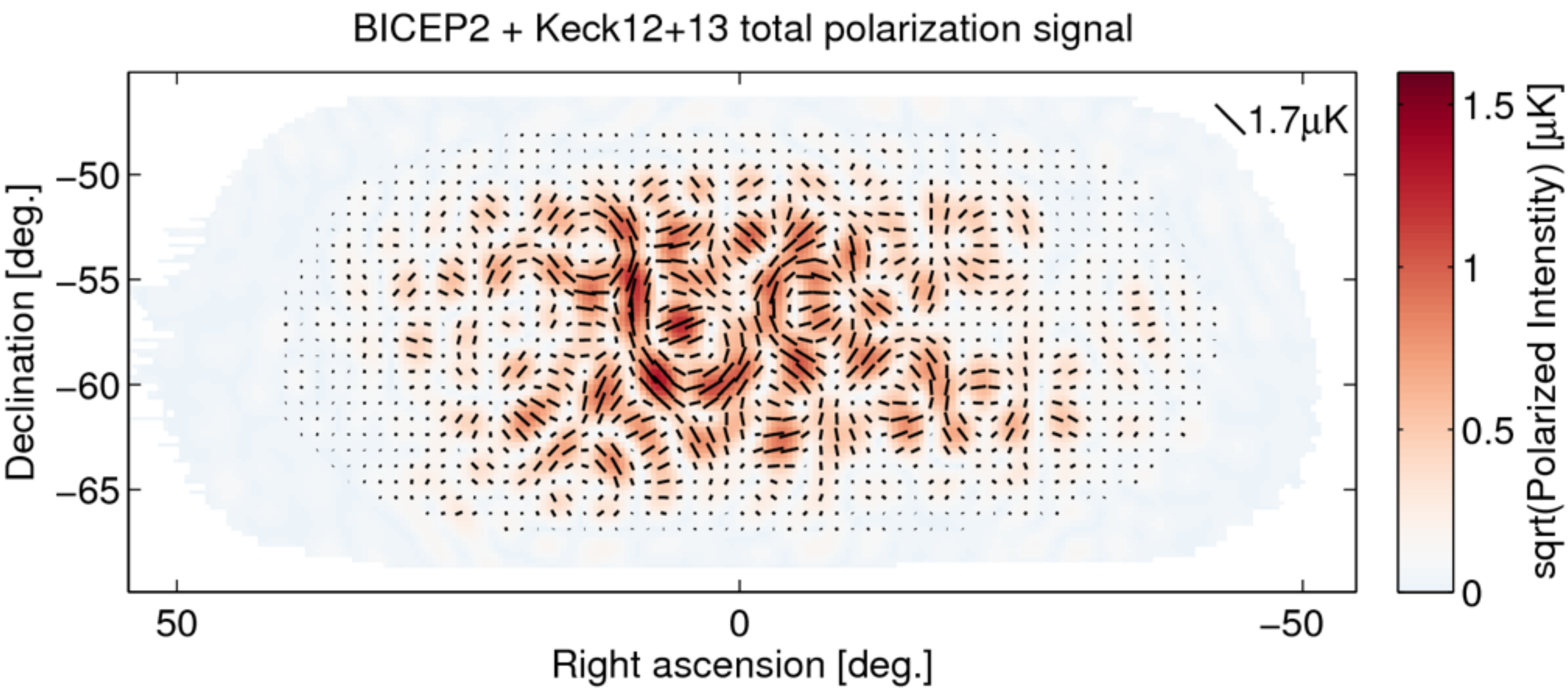
→ amplitude directly proportional to r

BICEP2 maps



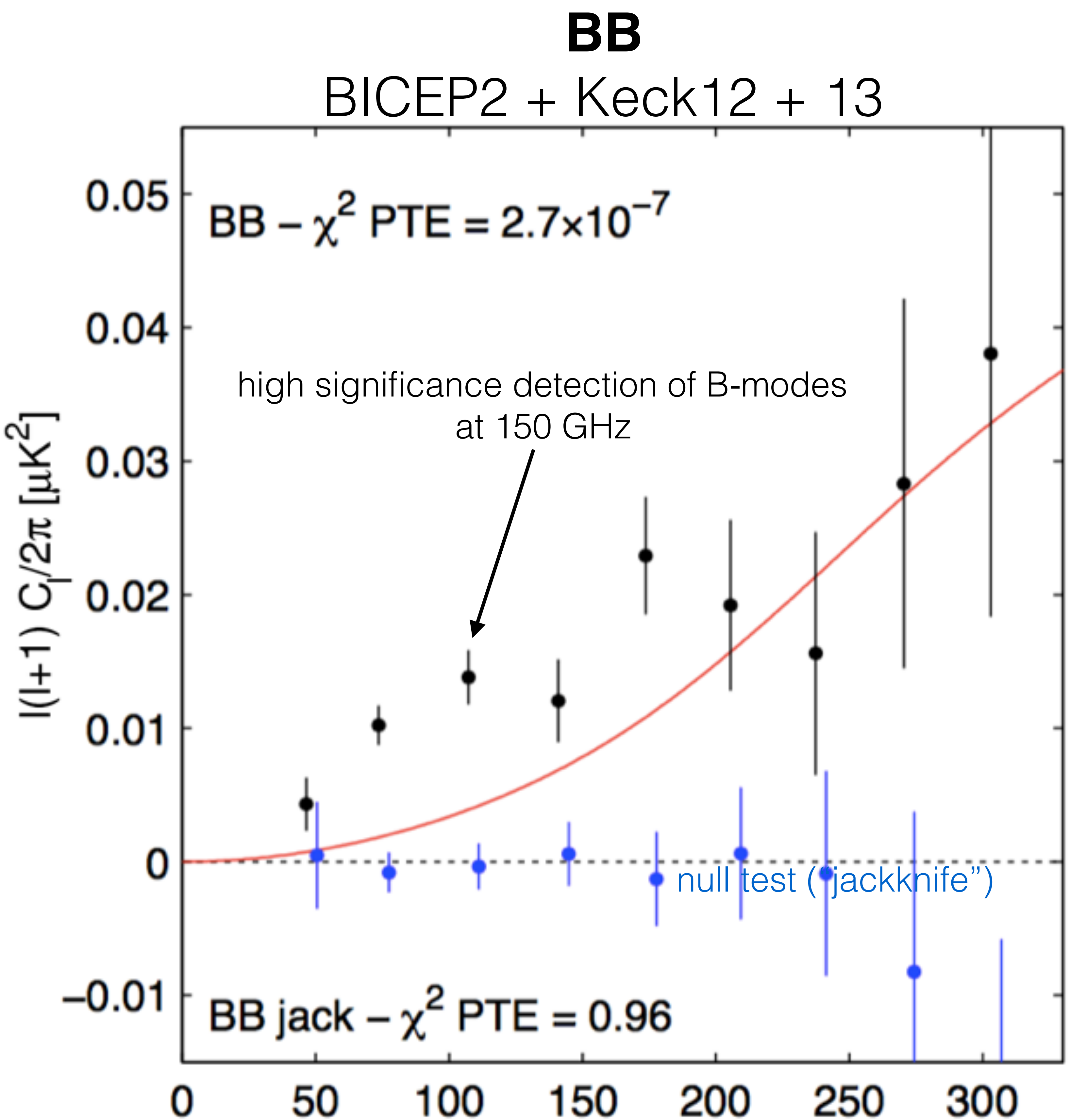
The BICEP/Keck Collaboration

Total Polarization



The BICEP/Keck Collaboration

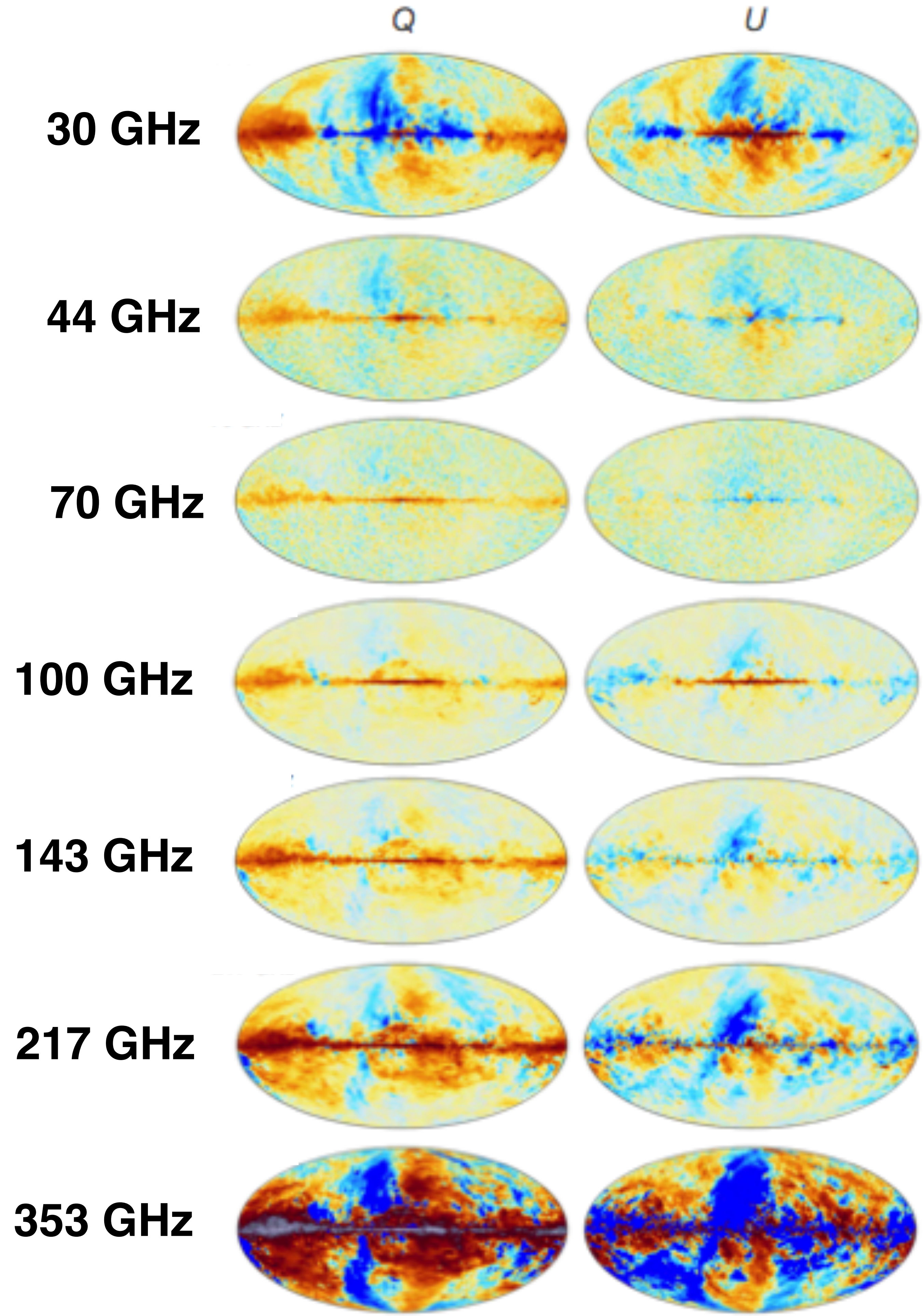
Using all data collected through 2013



Polarized galactic **synchrotron** dominates at low frequencies

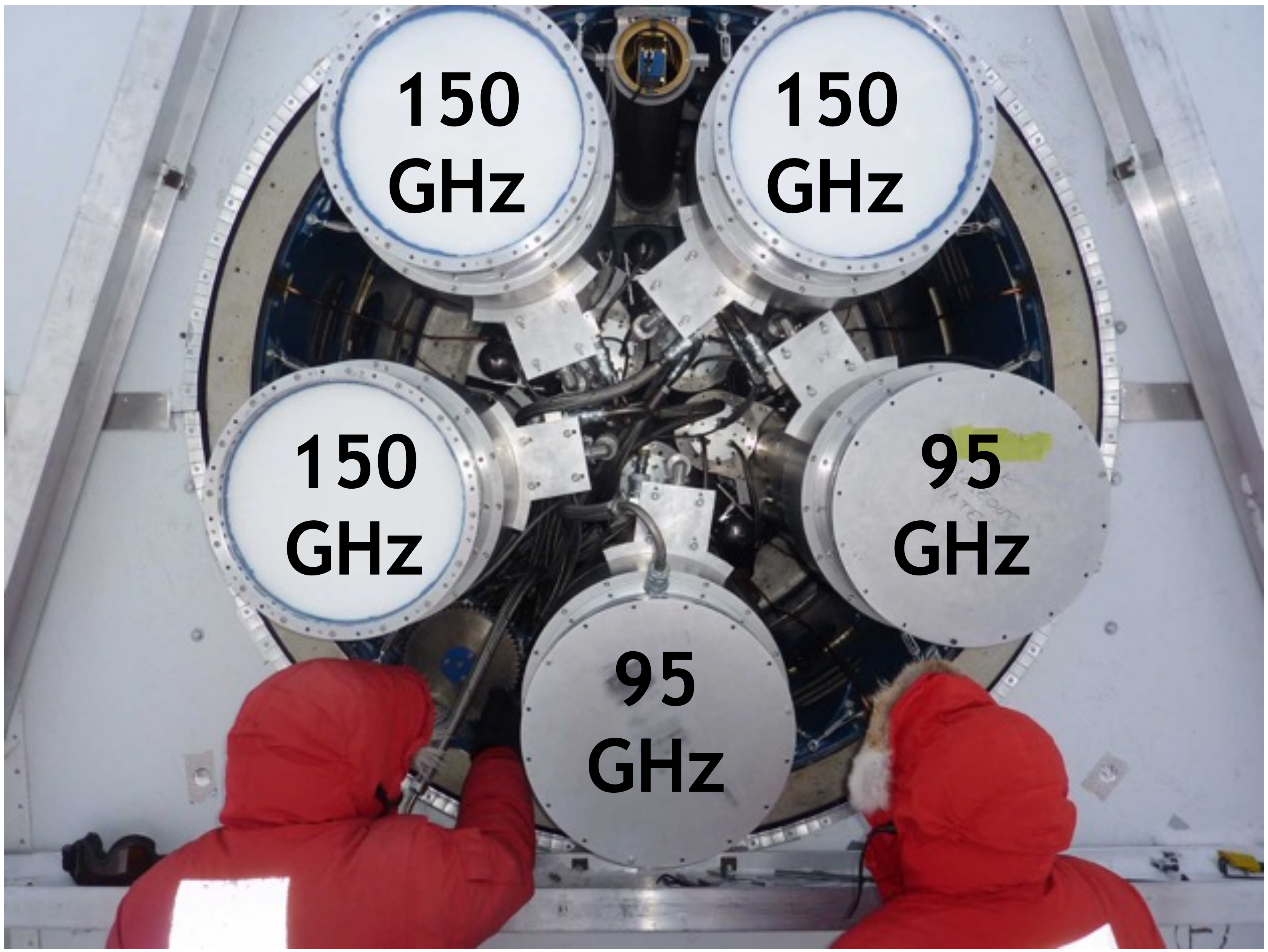
Polarized Galactic Foregrounds as seen by the Planck satellite.

Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields dominates
at high frequencies



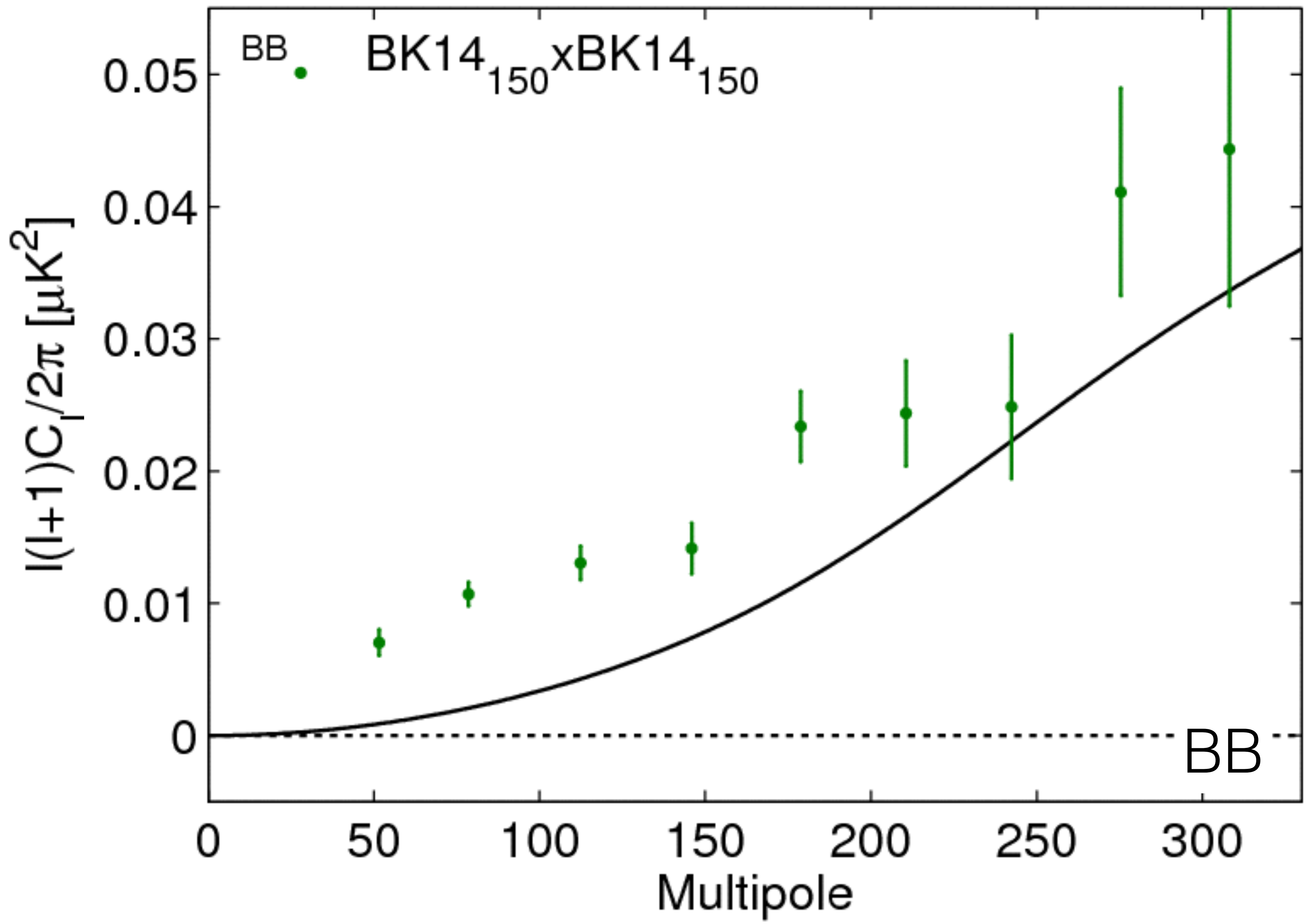
The BICEP/Keck Collaboration

Keck Array Frequency Coverage



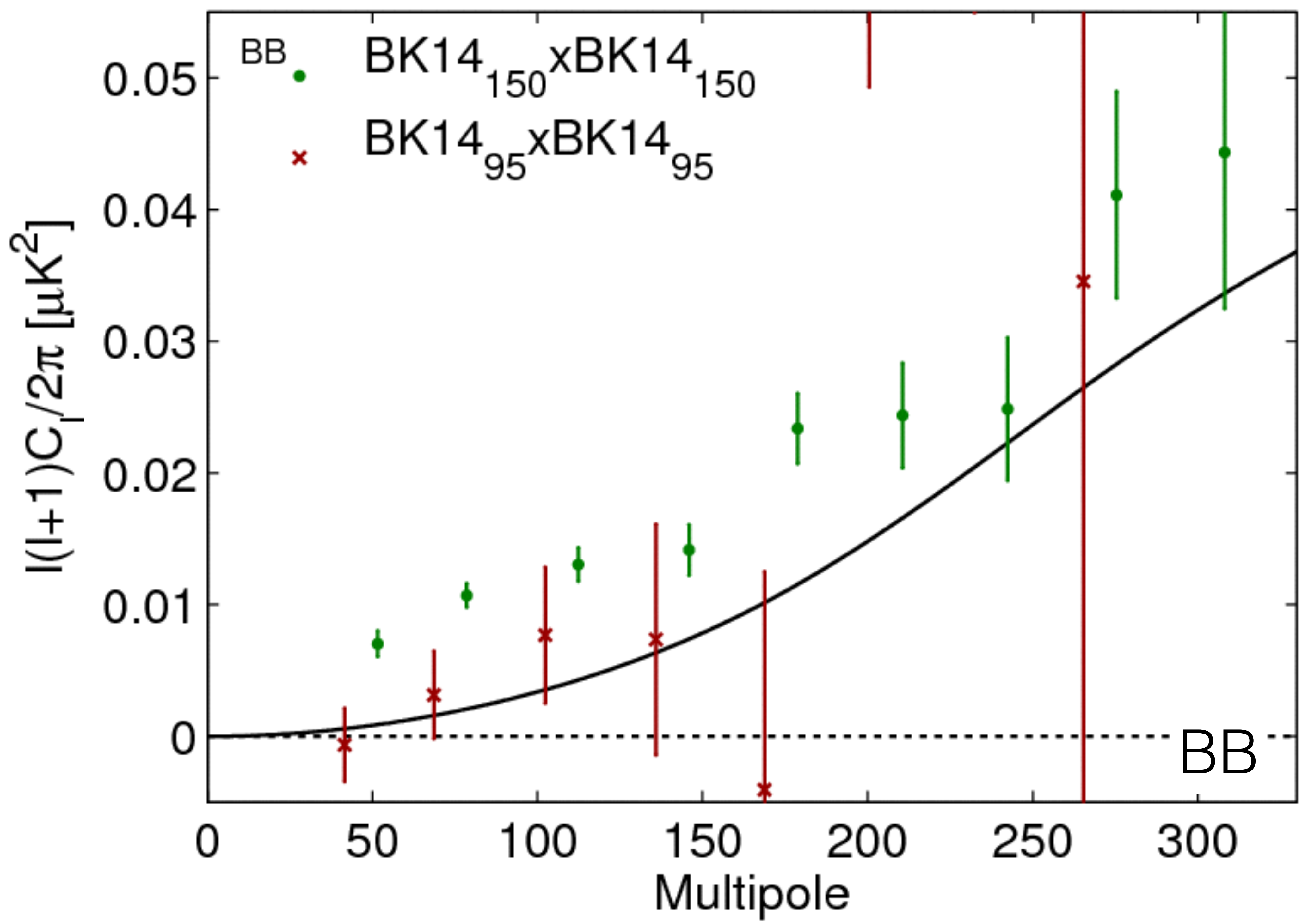
2014

BICEP2 + Keck BB auto and cross-spectra

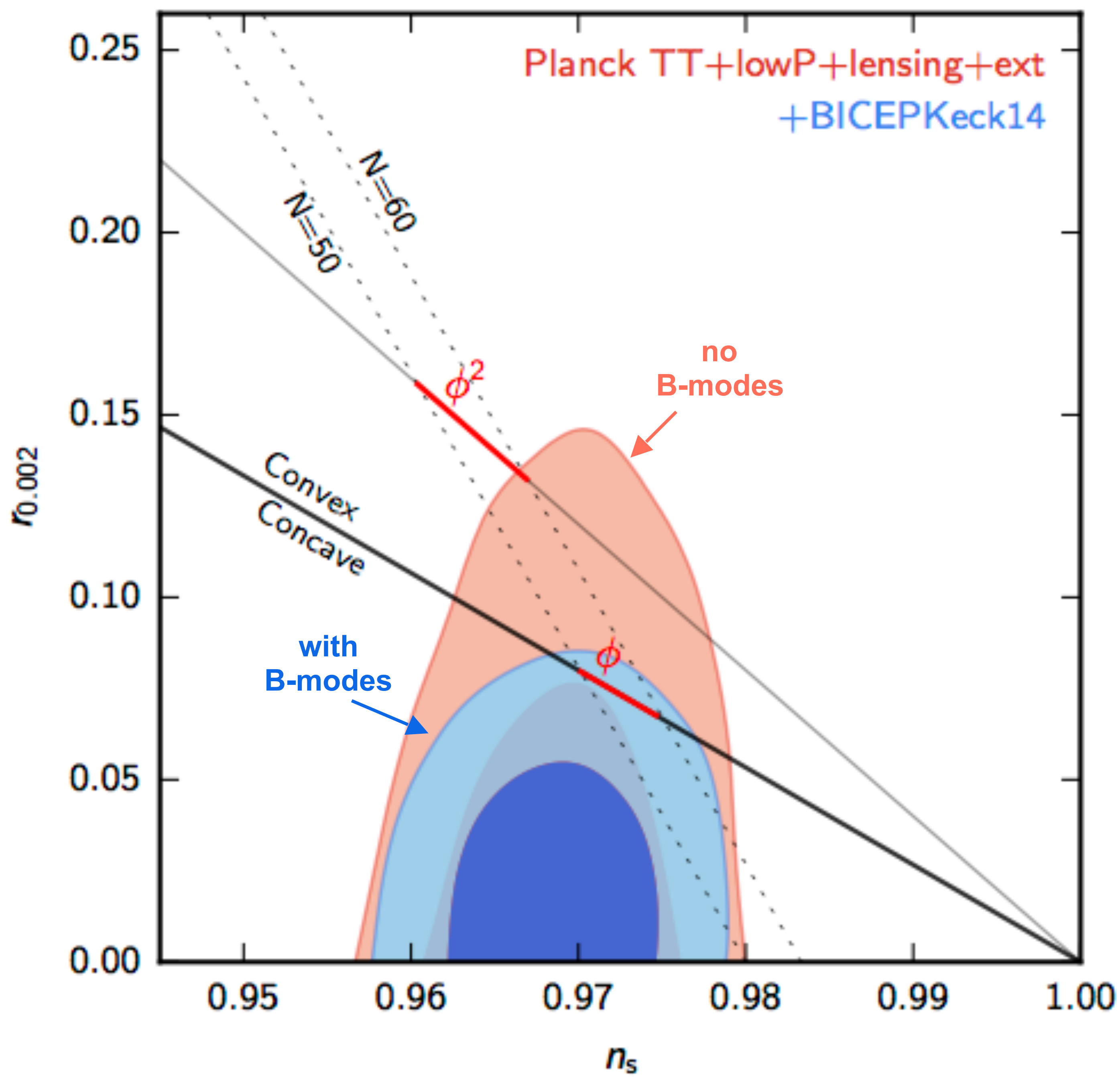


The BICEP/Keck Collaboration

BICEP2 + Keck BB auto and cross-spectra



Adding in temperature



$r_{.05}$ < 0.07

(best limits)

The BICEP/Keck Collaboration

The current push is to continue making very deep maps at many frequencies to disentangle galactic foregrounds from the CMB.

Thanks!